Bridging the land-sea divide: links, interactions, and trade-offs for food security and sustainability

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This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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Statement of co-authorship

Throughout the publication chapters of this thesis (2-5), the pronoun 'we' is used in place of "I". While I attest that this thesis is my own and was the primary researcher developing the scope, data collection, synthesis, analysis, and writing each chapter, the preferred use of 'we' is consistent with the collaborative nature of the works included within and recognizes the input from co-authors.

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Assoc. Prof. Blanchard made key contributions to article structure, narrative, and content through iterative review processes with Mr. Cottrell contributing approximately 8% of the articles' final narrative and structure. Dr. Fleming, Dr. Fulton, Dr. Nash and Prof. Watson contributed equally to adding content and providing perspective and considerations for the articles' narrative (~3%).

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Assoc. Prof. Blanchard provided important perspectives from salmon industry meetings on novel and plant-based feeds, the placement of this work within the wider aspects of this thesis, and with key restructuring suggestions across the manuscripts content (~8% of final content).

Prof. Halpern and Dr Metian provided equally important perspectives on how this work is situated within the wider body of work addressing aquaculture feeds and provided key structural and content contributions to the articles' narrative and presentation (~4%)

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Assoc. Prof. Julia Blanchard was integral to research planning, study design, narrative evolution and structuring (~8% of final content)

Dr. Nash and Prof. Halpern were central to project planning and design and provided key contributions to the manuscript's narrative, particularly surrounding aspects of resilience. Dr Remenyi provided important technical guidance for coding and data analysis surrounding uncertainty as well as figure preparation supplementary to the papers' main body. Each author contributed approximately 4% of the paper's final content.

Dr. Fleming an Dr. Fulton and Dr. Hornborg lent key insight in terms of food system resilience at ecological and social levels. Dr Corney lent expertise on climate uncertainty and approaches to addressing this in the qualitative analysis conducted within. Ms. Johne assisted with qualitative analysis of shock drivers. Each author here contributed approximately 2% to the paper's final content.

All authors contributed to narrative development and paper structure.

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Chapter 5 – Addressing land-sea shifts in Australian consumption for food system sustainability

R.S. Cottrell (80%), A. Fleming, E.A. Fulton, H.E. Froehlich, K.L. Nash, R.A. Watson, J.L. Blanchard

Mr. Cottrell was the primary author responsible for study design, data analysis and synthesis and manuscript writing contributing approximately 80% of the paper's final content.

Assoc. Prof. Blanchard assisted in manuscript structuring and direction, providing important expertise for data analysis, contributing approximately 7% of total content.

Dr Fleming assisted with sentiment analysis of headlines where duplicate analysis were required to minimize individual bias in analysis and provided key direction and edits for manuscript narrative (~5% of final content).

Dr Fulton lent critical expertise in Australian food systems knowledge, particularly surrounding the state of domestic capture fisheries and aquaculture sectors. Assist. Prof Froehlich provided methodological guidance and suggestions for placement of work within the wider literature. Dr Nash and Prof. Watson contributed equally to providing valuable edits to the manuscripts text and structure to strengthen the narrative. All authors here contributed approximately 2% to the final content of the paper.

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Abstract

Ensuring food security for a human population growing towards 10 billion under the pressures of demographic, social and climate change is a huge challenge. Advances across all terrestrial and aquatic food sectors are necessary for more efficient and sustainable production. Agriculture produces the majority of human food, but capture fisheries are crucial for the nutrition and livelihoods of many, and aquaculture will necessary if we are to supply increasing global demands for fish. However, research and policy directed toward improving food security are largely siloed within food sectors. Using data synthesis and modelling approaches, this thesis explores the range of links and interactions among terrestrial and aquatic food sectors and their significance for sustainable development. I show how terrestrial and aquatic food systems interact through interdependencies for animal feeds, shared space or the flow of natural subsidies, linked human resource use, and feedbacks with the climate. By switching to novel ingredients such as algae or insects, I demonstrate how fed aquaculture can substantially reduce its demand for small pelagic 'forage' fish used as feed, even after accounting for trade-offs for fish growth and human health benefits. I address the risks of single-sector perspectives to food systems research by highlighting how the drivers of sudden production losses (such as extreme weather) can unexpectedly displace human resource use, or create linked challenges for adaptation, across land and sea. Further, I illustrate how changing human consumption can shift food demands across the land-sea divide, illuminating challenges, and opportunities for sustainability. Ultimately, this thesis highlights how single-sector approaches to food system research can create blind-spots in our understanding of sustainability and how threats may be propagated or diffused across land and sea.

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Table of Contents

List of figures and tables

Chapter 1

1. General introduction

Food security exists when all people have physical, social, and economic access to sufficient, safe, and nutritious food at all times to meet their dietary needs and food preferences for an active and healthy life (FAO 1996). This concept is founded on four main principles – that enough food is available; food can be accessed, safely utilized; and that supply remains stable. Given the temporal element of stability, recent studies now advocate for a fifth element to be incorporated – sustainability - to reinforce how the needs of the present population should not compromise those of future generations (Berry et al. 2015). Yet each of the pillars of food security, including sustainability, are being challenged under global change by the cumulative pressures of shifts in population, demography, and climate.

1.1. Food security challenges under global change

As the human population increases towards 10 billion by 2050 (United Nations Department of Economic and Social Affairs Population Division. 2019), the challenge of sustainably producing sufficient food will be amplified as consumer affluence grows. Increased per capita wealth is associated with greater proportions of animal-based foods (Tilman & Clark 2014, Godfray, Beddington, et al. 2010, Willett et al. 2019) which typically require more land, water, energy, and inputs for production and hold greater potential for environmental impacts from eutrophication, biodiversity loss, and acidifying and greenhouse gas emissions (Poore & Nemecek 2018, Hilborn et al. 2018, Davis et al. 2016). This is largely due to the inherent inefficiencies in the trophic energy transfer between primary producers, animal-based feeds, and the animals consumed for food (Godfray et al. 2018, Bonhommeau et al. 2013). So while population is expected to increase by approximately a third in the next 30 years, shifts in human diets indicate we will need to produce between 50-100% more food, or make better use of the ~30% of food that is currently wasted (Alexandratos & Bruinsma 2012, Godfray, Beddington, et al. 2010).

Inevitably there are biophysical limits to how much food we can produce from the Earth. While food systems are fundamental to human nutrition and livelihoods they are also major global drivers of environmental degradation (Springmann et al. 2018, Godfray et al. 2018, Watson et al. 2015, Willett et al. 2019). Agriculture produces the majority of human food but is thought to be the primary reason for our transgression of safe planetary boundaries for biodiversity loss and disruption of the nitrogen cycle – and at high risk of doing the same for freshwater use and land-use change (Campbell et al. 2017, Steffen et al. 2015, Rockström et al. 2009). Capture fisheries are a key source of livelihoods and nutrition for millions worldwide, particularly those in low-income countries and small-island developing states (Béné, Barange, Subasinghe, Pinstrup-Andersen, Merino, GI Hemre, et al. 2015, FAO 2018, Golden et al. 2016). But overfishing remains a pervasive threat to marine biodiversity in the global ocean and ubiquitous declines in fisheries catch per unit effort signal a dwindling resource (Rousseau et al. 2019) – and the influence of fishing on fish population collapses remains very difficult to untangle from the influence of climate change. Furthermore, food security contributions from inland fisheries are unclear, and in many countries more significant than reported (Fluet-Chouinard et al. 2018). Fish consumption on the rise globally (FAO 2018) and the continued rise of aquaculture will be important for meeting increasing demands. By decoupling of production to natural background variation in environmental conditions, aquaculture can provide increased control over the stability and quality of supply. Nonetheless, sustainable sourcing of feeds (Merino et al. 2012, Froehlich, Jacobsen, et al. 2018, Fry et al. 2016, Troell, Naylor, et al. 2014, Naylor et al. 2000a, Cao, et al. 2015, Naylor & Burke 2005), nutrient pollution surrounding farms (Edwards 2015), intersectoral conflicts in coastal zones (Clavelle et al. 2019, Cottrell et al. 2017, Bhat & Bhatta 2004) and genetic introgression into wild populations (Lehnert et al. 2013, Butler et al. 2005, Jonsson &

Jonsson 2006, Bartley et al. 2000) are important issues aquaculture must address. If we are to meet future food demands, we must do so without fundamentally undermining the ecosystem services on which we depend for food production.

Inequality in the distribution of, and access to food, presents a significant barrier to more widespread food security. We produce enough food to feed the global population at present but over 800 million people still live in a state of hunger and many more suffer from micronutrient deficiencies (FAO IFAD UNICEF WFP & WHO 2019). Meanwhile greater access to meat and empty calories such as sugars and refined fats have contributed to rapid global increases in the prevalence of other forms of malnutrition associated with over-consumption such as obesity and related chronic diseases (Tilman & Clark 2014, Popkin et al. 2012, Willett et al. 2019). Gender inequality, persecution, uneven trade policies, lack of access to global markets, environmental volatility and food waste along different stages of the supply chain drive complex patterns and differences in food access from household to international scales (FAO IFAD UNICEF WFP & WHO 2019, Godfray, Beddington, et al. 2010, FAO IFAD UNICEF WFP & WHO 2017, Buhaug et al. 2015, Bureau & Swinnen 2018, Agarwal 2018).

While the most acute losses in food access often occur as the result of catastrophes such as drought, floods, or war (FAO IFAD UNICEF WFP & WHO 2017, Buhaug et al. 2015) most food insecurity exists as a result of chronic poverty (Barrett 2010). To address persistent access challenges, more widescale transitions across human diets and waste management are required. Shifting human diets in developed nations towards greater proportions of fruit, vegetables, whole-grains, and efficient forms of animal production such as poultry and fish can liberate food away from livestock feed and toward human consumption while improving human health benefits from consumption (Willett et al. 2019, Foley et al. 2011). Similarly, technological development along supply chains in developing countries can prevent food wastage that may be as high as 40%. Even small reductions in this waste among the poorest nations can significantly reduce the need to produce more food but use current production levels more efficiently (Foley et al. 2011). Yet a lack of coordinated approaches to dietary and waste reduction transformations and the needs for investment flows across multiple sectors and governmental and food system actors still remain a substantial barrier for change (Willett et al. 2019).

Addressing increasing food demands or inequality in food distribution are often viewed as opposing approaches to solving food insecurity, but they are intrinsically linked. For example, in Sub-Saharan Africa, where the greatest burden of hunger persists, unfavourable environmental and economic conditions for food production, patriarchal culture, poor education, violent conflict, above-average disease prevalence, and corruption surrounding resource use and foreign aid create considerable barriers to equitable food access (Ehrlich & Harte 2015a, Barrett 2010). But the rapid growth in population and food demand compound each of these problems –burgeoning cities with a growing undernourished and unemployed population do not create favourable conditions for democracy to establish (Ehrlich & Harte 2015a, Barrett 2010). Access inequalities are maintained when population demands outpace basic public services, livelihoods are negatively affected by environmental degradation, and focus turns to survival rather than striving for social justice (Ehrlich & Harte 2015b). Even in developed nations such as the United States, corporate and political interest in food systems can drive disinformation, cuts to food assistance programs, and undermine the nutritional value of food produced for domestic and international markets (Ehrlich & Harte 2015a, USDA 2019). Thus, the social, economic, political, and environmental foundations that underpin our society fundamentally influence our capacity to both produce *and* distribute food.

Climate change further complicates ambitions for food security by generally undermining production. Changes to temperature and precipitation regimes influence food availability, access, utilization and stability across all food sectors via thermal stress, extreme weather events, changing disease and pest prevalence, changes to species distribution, and price inflation in response to resource scarcity (Schmidhuber & Tubiello 2007, Wheeler & von Braun 2013, Chakraborty & Newton 2011). Extreme weather events that reduce food production can also drive political instability and conflict which in turn feeds back by reducing access to food (Kelley et al. 2015). As a result of the interaction between extreme weather, violent conflict and the subsequent economic slowdown, the global prevalence of hunger has increased for three consecutive years against the long-term trend (FAO IFAD UNICEF WFP & WHO 2017, FAO IFAD UNICEF WFP & WHO 2019). With 36 million more people living in hunger than in 2015, the challenge of achieving global food security looms large.

1.2. Toward more sustainable food production on land and sea

In recognition of the complex, intertwined challenges global change poses for our planet and its people, 193 countries ratified a global sustainability agenda in 2015 – the United Nations Sustainable Development Goals (SDGs) (United Nations 2015a, Figure 1).

Figure 1 – the United Nations Sustainable Development Goals (SDGs) (taken from United Nations 2015a)

Across the 17 SDGs are 169 integrated and indivisible targets that address a broad range of social, environmental and economic dimensions (United Nations 2015a) and our progress towards many of them will be closely linked to food systems (FAO 2018). Ending hunger, achieving food security, promoting sustainable agriculture (SDG 2) and the associated targets to end malnutrition directly lay the foundation for achieving multiple SDGs. For example, improved nutrition directly influences health and wellbeing (SDG 3), contributes positively to livelihoods which in turn leads to financial stability (SDG 1), better education (SDG 4), greater gender equality (SDG 5), increased economic productivity (SDG 8), and more responsible production practices (SDG 12-14) (FAO IFAD UNICEF WFP & WHO 2019). Yet meeting increasing food demands through conventional intensification (high dependence on monoculture, external inputs for fertilizers and pesticides, and few fish species) of food systems will erode the very resource bed our food depends on and the disparities in poverty, health, equality, and hunger among us will likely widen (Garibaldi et al. 2016).

Fundamental restructuring to how we produce food is necessary and a huge body of research has sought and elucidated key improvements needed across terrestrial and aquatic food systems. Doubling productivity for farmers and fishers while transforming food systems to be more climate-resilient and improve the diversity of what is grown and harvested are concepts at the heart of the goal for zero hunger, SDG 2 (United Nations 2015a). To ensure these targets do not hinder other goals for environmental protection and social equity, any increase in food production needs to come from existing agricultural land and far greater efficiency in the ocean.

Rethinking production practices to better account for and support the ongoing delivery of ecosystem services is crucial to address multiple sustainability targets affected by food systems. On land, nutrient and water, pest control, and pollination provisioning are ecosystem services which, through landscape simplification, conventional agricultural intensification has eroded (Bommarco et al. 2013, Garibaldi et al. 2016). Reducing tillage, increasing soil cover with crop residues and crop rotation may help boost crop yield while reducing soil erosion and the need for agrochemical inputs (Pittelkow et al. 2015). Integrating trees in crop (agroforestry) or livestock systems (silvopastoralism) can increase yields and stability of production through promoting greater soil carbon storage, inputs and nitrogen fixation, erosion control, shelter and microclimate stability (Duru et al. 2015). Benefits to these approaches also spill over into livelihoods and the environment. These features encourage faster recovery after extreme events and can deliver alternative food and income sources from fruit, timber, and fuel while providing wildlife corridors and refugia (Waldron et al. 2017, Bhagwat et al. 2008). Growing hedgerows, riparian buffers, forest patches and a greater diversity of crops also provide greater nesting resources for pollinators and predatory insects valuable to biological control of pests (Stenberg 2017, Bommarco et al. 2013, Kovac-Hostyanszki et al. 2017). Diverse intercropped production units are less susceptible to disease outbreaks than monocultures and central to integrated pest management - a key strategy in addressing the influence of pests of food production and safety while minimizing the environmental impacts of pesticides (Stenberg 2017). Higher diversity of crop production has also been found to stabilise food production at national levels (Renard & Tilman 2019).

While I recognize other work has established that more conventional intensive land sparing activities than those described here may help limit agriculture's impact on surrounding biodiversity (Phalan et al. 2016), these may only continue to be effective in the future if soil health is maintained for instance. Yet in a world of increasing climatological and meteorological volatility, maintaining agricultural resilience (the capacity of the agricultural system to maintain its structure, function, and processes in the face of disturbance and change (Schipanski et al. 2016)) may require the more dramatic shifts I discuss here. Increasing the diversity (including regional diversity) of what we grow, reducing the need for external inputs using ecological principles, and placing greater agency and adaptive capacity in the hands of small-scale producers may help counter the threat from environmental, resource and economic volatility (Schipanski et al. 2016). The range of the ecosystem-based approaches to agricultural production mentioned above aim to do just that as fundamental principles of 'Sustainable Intensification', advocating for regenerative, low-input farming that may be adapted to ensure that agriculture remains environmentally, socially and nutritionally appropriate (Godfray & Garnett 2014, Garnett et al. 2013, Pretty 1997). Still, progress towards shifting terrestrial food production away from conventional intensification and adopting new practices has been slow. This largely because of uncertainty surrounding the economic benefits of alternatives (Garibaldi et al. 2016) and differences among the social identity of farmers, technological availability, farm size, profitability of crops grown, farmer education level, and local community (Bravo-monroy et al. 2016). Altering entrenched behaviours remains a challenge across different facets of the food system (Godfray & Garnett 2014).

As in agriculture, ecosystem-based approaches are now recognized as fundamental to good management of aquatic food production systems (Soto et al. 2008, Nunes et al. 2011, Costa-Pierce 2008, Link 2002, Pikitch et al. 2004). Ecosystem-based fisheries management (EBFM) or ecosystem-approaches to fisheries (EAF) management aim to prevent ecological degradation from fishing while still maintaining nutritional and socioeconomic benefits of fisheries (Pikitch et al. 2004, Link 2002, Cury et al. 2005, Jennings 2005, Jennings et al. 2014, Garcia & Cochrane 2005). The concept of 'balanced harvesting' has been introduced in recent years to address this paradigm shift in management thinking. Balanced harvesting proposes moving towards lower fishing selectivity (whether size, species, season, or stock, sex, or spatial), distributing harvest more evenly across the aquatic food web thought to reduce ecosystem-wide distortion and trophic cascades, while reducing unused bycatch (Jacobsen et al. 2014, Garcia et al. 2012). Differences in the diversity of species caught, fishing gears and power of fleets, technological advancement, stakeholder priorities, and preferences within local and distant markets present several technical and socioeconomic hurdles for balanced harvesting and no single approach can address these (Fulton et al. 2014, Zhou et al. 2015). As a result, much contention surrounds balanced harvesting, with some questioning the validity of the ecological principles, ecosystem models, or real-world examples on which the concept is based and defended (Froese et al. 2016). Nonetheless, using ensembles of different simulation approaches for Management Strategy Evaluation continues to provide valuable insights into how to optimize fisheries management among social, economic, and ecological objectives in the face of uncertainty (Fulton et al. 2014). Implementing aquatic reserves and zoning measures are can also protect fish habitats from fishing pressure and provide livelihood, nutritional and equity benefits for fishers (Halpern et al. 2010, Mascia et al. 2010), although their efficacy is highly dependent on robust design and sufficient financing (Edgar et al. 2014, Gill et al. 2017).

Despite greater recognition of the need for EBFM/EAF and the potential for using greater resource efficiency, it is unlikely that capture fisheries will be able to sustainably fill the gap between current production and projected demand for fish (as feed or food) by 2030 under global change (World Bank 2013). Global catch has remained relatively stagnant since the early 2000s (FAO 2018) with some reconstructions suggesting it could be in decline (Pauly & Zeller 2016). This apparent stability has come with a greater incursion into the marine environment as global fishing distances have doubled but yields have dropped to 20% of those seen in 1950 (Rousseau et al. 2019, Tickler, Meeuwig, Palomares, et al. 2018). Capture systems also face several other sustainability challenges such as illegal, unregulated and unreported fishing activities (Watson 2017, Fluet-Chouinard et al. 2018) and the pervasive use of slavery within distant-water operations which are a symptom of broader institutional and national governance issues (Tickler, Meeuwig, Bryant, et al. 2018, Vandergeest et al. 2017, Nakamura et al. 2018).

In contrast, aquaculture production has continued to grow rapidly since the 1980s. Total global aquaculture production exceeded 110 million tonnes of biomass in 2017, 80 million tonnes of which was food ‘fish’ (including finfish, molluscs, crustaceans, echinoderms, frogs and other aquatic organisms and represents near to biomass from capture fisheries) and 30 million tonnes of aquatic plants and seaweed (FAO 2019a, FAO 2018). Over 400 aquatic ‘species items’ (some are aggregated in broad groups when reported) were produced through aquaculture in 2017 across 194 countries and principalities, although over 96% of production is held by just 20 countries, the largest of which are in Asia (FAO 2019a; see Figure 4 in Chapter 2). Inland freshwater aquaculture dominates the global food contribution from aquaculture and the majority of this is finfish, of which Chinese carp are the most prominent. In contrast, shelled molluscs such as mussels and oysters represent approximately 60% of marine or brackish water production with the surplus composed of crustaceans and finfish (FAO 2018). Inland production in Asian countries, particularly China, serves an important role for domestic food supply and an important source of livelihood and food security in the country of production (FAO 2018, Cao et al. 2015, Chiu et al. 2013, Edwards 2015). Whereas, in Europe or the Americas, marine aquaculture (or 'mariculture') dominates production and many of the goods produced are exported and highly traded (FAO 2018).

Problems of disease, nutrient pollution, genetic escapes, and low input efficiency plagued the sector early in its expansion (Naylor et al. 2000b, Naylor et al. 2009). But much has changed, and aquaculture holds great potential for sustainable production of animal protein. Compared to terrestrial animals, fish and aquatic invertebrates are generally more efficient at converting feed resources into edible biomass and often with lower environmental impacts (Poore & Nemecek 2018, Hilborn et al. 2018, Froehlich, Runge, et al. 2018, Tilman & Clark 2014, Pelletier et al. 2011). Albeit with considerable variation around species based on their farming or capture methods (Hilborn et al. 2018). There is also a far greater diversity of what is grown compared to pastoral systems on land (Troell, Naylor, et al. 2014) and this provides opportunities to exploit potential symbioses support the functioning of production units and the ecosystems in which they are embedded. For example, growing extractive species such as mussels and seaweeds have direct benefits for water quality and carbon storage in inland and marine systems (Edwards 2015). When coupled to the culture of fed species (e.g. finfish, shrimp) and detritivores (e.g. snails, sea cucumbers) these integrated multi-trophic systems (IMTA) can actively reduce nutrient pollution from the filtering of faeces, feed, and pseudofaeces, and the absorption of dissolved nutrients. Furthermore, such a system generates a diverse range of foods for consumers and producer livelihoods (Diana et al. 2018).

IMTA has been applied with positive results at even the largest commercial scales and could provide a valuable avenue for increasing food production with far greater environmental efficiency (Buck et al. 2017, Kleitou et al. 2018). Key challenges remain, however, particularly in a marine setting with the growing need to place aquaculture further offshore to avoid coastal conflict among various other resources uses such as fishing, transportation, recreation, or energy (Tiller et al. 2012, Troell et al. 2009). Suitable siting away from high energy waters, appropriate conditions for extractive species to thrive, control of fouling organisms, economic and technological viability of husbandry, investment potential, poor public perceptions, legislation, markets for co-products, technology and expertise still limit its widespread adoption (Kleitou et al. 2018, Troell et al. 2009, Barrington et al. 2009, Chopin et al. 2012, Alexander et al. 2016, Alexander et al. 2015, Buck et al. 2017, Buck et al. 2018).

Diversified production systems feed positively into other food security and sustainability targets such as improving food access for and empowerment of women as well as greater community cohesion and resilience to external shocks (Schipanski et al. 2016, Cinner et al. 2012, Allison & Horemans 2006). For example, the different forms of income generation that are possible with agroforestry encourage greater partitioning of workloads across a household (Cafer et al. 2015, Asher & Shattuck 2017, Degrande & Arinloye 2014, Gebrehiwot et al. 2018). Indigenous fruit trees and planting of fodder for milk production can generate important female-led enterprises that increase women's capacity to produce and procure food (Kiptot et al. 2014). Furthermore, on-farm trees generate considerable quantities of fuelwood reducing the need for household members (particularly women) to walk large distances for firewood, releasing time for education or other livelihood activities and engage women across different aspects of the timber crop supply chain (Waldron et al. 2017, Sharma et al. 2016). Similarly, female-led seaweed farming conducted in parallel to small-scale fisheries has increased livelihood engagement across household members and significantly boosted attainable household income for coastal fishing communities worldwide (Periyasamy et al. 2014, Msuya 2006). Homestead pond aquaculture integrated into agricultural settings also promotes greater opportunities for women to produce and access fish, complementing other household production activities (Castine et al. 2017, Ahmed &

Waibel 2019). Critically, greater capacity for women to drive decision-making over resource use tends to increase household food consumption and improve child nutrition, particularly during times of crisis such as conflict or environmental catastrophes (FAO IFAD UNICEF WFP & WHO 2017, FAO 2012).

Technological solutions will be ever more important for increasing food availability and access under global change and are being implemented across all stages of food supply from production through distribution. Sensors and nanotechnology are increasingly being used for understanding soil conditions, driving on-farm machinery, timing animal feeding or monitoring livestock health and detecting plant disease (Godfray, Beddington, et al. 2010, Gebbers & Adamchuk 2010, Mahlein 2016, Duhan et al. 2017). Advances in genetic science are helping with understanding disease emergence, improving resistance to environmental volatility, tracking illicit wildlife trade, increase production limits, or creating more sustainable feeds (Marshall 2014, Stentiford et al. 2017, Napier et al. 2019, Bunholi et al. 2018, Godfray, Beddington, et al. 2010). Wireless technologies and machine learning are also being to reducing food wastage during transportation, and increasing mobile coverage for poorer communities are growing steps towards improving equitability in food access at a global level (Wantchekon & Riaz 2019, McCarthy et al. 2018).

Different technological solutions are being employed in different regions or across different scales. For example, for countries in arid and semi-arid regions where insufficient rainfall and high temperatures often compound problems of drought and food insecurity, solar-powered solutions have great potential. Solar desalination can reduce demands on agricultural freshwater use in coastal nations and is already being employed in Spain and across the Middle East. Solar-powered evaporative cooling in greenhouses shows promise in increasing the shelf-life of fruits and vegetables and reduce wastage along the supply chain (Sibanda & Workneh 2019). Speed breeding in crops, through altering the light quality, light intensity and daylights hours over plants in high-density indoor facilities can greatly increase yields and these processes can be augmented by translucent solar panels that transmit wavelengths most beneficial to plant growth (Liu et al. 2018, Hickey et al. 2019). Where crops are light-sensitive, genetic modification (GM) of specific genes may help improve tolerance to longer lighting regimes and thus encourage growth. Genetic tools are also aiding in the production of drought-tolerant crop species of maize, sugarcane, wheat and rice and their adoption is increasing rapidly across the globe (Marshall 2014). The potential for gene editing also transfers to livestock, particularly for disease resistance given the welfare and economic implications of mass mortality events such as those from African swine fever (Bruce 2017). GM Salmon are also being considered to produce fish more efficient in growth and feed use which may ultimately reduce pressure on both terrestrial and marine ecosystems for feed provision. As with all GM materials aiming to enter food systems, strict food safety assessments and challenges surrounding public opinion will be highly influential on the success of a product (Smith et al. 2010). Satellite technologies are now also being used to track the movements, effort and transhipments of fishing vessels globally (e.g. Dunn et al. 2018) allowing novel ways of detected illegal fishing and illicit trade activities that undermine resource management.

1.3. The need to integrate land and sea in food system research

Despite the vast and important body of work established to date, most research on how to improve food system sustainability tends to take a single-sector focus addressing development in either terrestrial or aquatic food sectors but rarely across realms. A significant body of work has focused on interactions among fisheries and aquaculture sectors (Arechavala-Lopez et al. 2015, Asche et al. 2001, Skjæraasen et al. 2010, Glover et al. 2013, Roberge et al. 2008, Clavelle et al. 2019). And while several studies have looked at cross-sector interactions from feed more recently (Jackson & Shepherd 2010, Troell, Naylor, et al. 2014, Froehlich, Jacobsen, et al. 2018, Froehlich, Runge, et al. 2018), there remains a paucity of multisector food system research.

Far more attention has also been paid to agriculture than aquatic food systems despite the importance of fisheries and aquaculture for nutrition and livelihoods in some of the world's poorest and food insecure populations (Arthur et al. 2013, Halpern et al. 2019). One reason for this disparity is the sheer scale of agriculture – terrestrial farming provides most human food and is responsible for approximately 25%of all anthropogenic emissions of greenhouse gases (Smith 2018). But there are also institutional and disciplinary-bound drivers of this skew. Academic systems tend to value discipline-specific research over interdisciplinary themes (Bromham et al. 2016). The ongoing transactional costs of overcoming language differences between scientists, increased time expenditure synthesizing methodological or epistemological contributions, or complications of accounting for research impact within departments can generate significant barriers for working across disciplines (Alexander et al. 2019).

Recent work highlights the risks inherent in single-sector approaches on food systems and security research. For example, agricultural commodities such as beef, chicken, pork, wheat, rice, and maize have received far more attention from environmental impact assessments than foods from the marine, freshwater, or wild terrestrial systems (Halpern et al 2019). For many nations, these under-assessed foods can represent substantial proportions of their total food production, and without these data, making informed food security and sustainability plans is impossible (Halpern et al 2019). In fact, many of these foods are conspicuously missing from food security strategies and policies in countries where they may make the greatest difference (Béné, Barange, Subasinghe, Pinstrup-Andersen, Merino, GI Hemre, et al. 2015). Terrestrial bias also exists within global sustainability frameworks. The 'Planetary boundaries' concept – which aims to define a safe operating space based on our understanding of how our activities influence the functioning and resilience of the Earth system (Rockström et al. 2009, Steffen et al. 2015, Campbell et al. 2017, Willett et al. 2019, Springmann et al. 2018) – minimizes the importance of the marine environment (Nash et al. 2017). Given global dependence on marine processes for the integrity of the biosphere, this is a considerable blind spot. Furthermore, recent work reveals how the full implications of climate change on food production are hidden when taking single sector approaches. Combining and contrasting projected fish and crop production using climate and ecosystem model assemblages reveals how most coastal countries may experience reductions in both terrestrial and marine production by 2050 under climate change (Blanchard et al. 2017, IPCC 2019a, IPCC 2019b). These trends are particularly important when livelihood diversification across multiple food sectors is often cited as an adaptation strategy in developing countries, but where the risk from these double jeopardies is highest (Blanchard et al. 2017).

Terrestrial and aquatic production systems do not exist in isolation of each other but are fundamentally linked within the earth system by natural and human processes. When working with an incomplete picture of an interlinked system, modifications to one sector to move toward more sustainable and equitable production may produce unseen trade-offs for food production and livelihoods in another. Combining terrestrial and aquatic sectors into research can help highlight where these trade-offs or co-benefits exist and whether they influence our progress toward sustainable development or not. Given the multidisciplinary range of challenges that food system growth presents, research that recognizes both social and ecological aspects of the food system is paramount.

1.4. Thesis objectives

The principal aim of this thesis is to highlight the importance of taking a multisector approach to food security research by providing a clearer picture of the links and interactions among agriculture, fisheries, and aquaculture and why these connections matter when trying to improve sustainability in our food system. To achieve this aim, this thesis has four main objectives.

1. Characterize the typology of links among food production systems on land and sea and their significance for food security and sustainable development
2. Quantify how interdependencies among food sectors (e.g. through feeds) can drive trade-offs for environmental, economic, or social outcomes and to what extent these hinder progress toward greater sustainability.
3. Identify linked challenges that connect terrestrial and aquatic food systems and their implications for the resilience of the global food system.
4. Understand how changing consumption patterns link land and sea and influence sustainable development of food systems.

1.5. Thesis structure

In this thesis, I address the aims and objectives above using an interdisciplinary approach, combining literature reviews, synthesis of large datasets, statistical modelling, time-series analyses, and sentiment analysis. I make use of a wide range of published and publicly available data to explore the social-ecological nature of food systems. This thesis consists of four central chapters that have been written for individual publication in academic journals, and consequently, there is some repetition regarding the framing of food system sustainability or challenges under global change among the chapters.

Chapter 2 is a comprehensive systematic review that lays the foundation for discussion in subsequent chapters. In this chapter, I identify a typology for links among agriculture, fisheries, and aquaculture by reviewing and synthesizing published literature (journal articles, book chapters, reports) with food production data to populate conceptual models of food security and biodiversity implications of land-sea connectivity. I identify four categories for links among food sectors on land and sea; ecosystem connectivity, feed interdependencies, livelihood interactions and climate feedbacks This chapter was published in *Global Change Biology* in 2018.

Chapter 3 investigates potential trade-offs from feed interdependencies between land and sea. I investigate the potential for novel aquaculture feeds to ease pressure on marine ecosystems under aquaculture growth as demand for forage fish (small pelagic fish used for fishmeal and oil) in feeds increases. By combining global aquaculture production data with published information on fed species diet compositions, feed efficiencies, and industry growth scenarios I calculate projected demand for forage fish by 2030 and compare this to historical demand. Using a meta-analysis, I collate experimental data on the influence of fishmeal and oil on the growth efficiencies of fed farmed species and the nutritional value of their tissues. I illustrate how, although shifts away from marine-based feeds to terrestrial and novel ingredients can negatively impact growth and nutritional value in farmed fish and invertebrates, employing conservative replacement thresholds minimizes these trade-offs and substantially reduces forage fish demand into the future.

In Chapter 4, I investigate to what extent livelihood interactions and shifts in human resource use connect land and sea during or in response to extreme or unpredictable events such as drought or aquaculture disease outbreaks. By quantitatively identifying sudden losses to food production (or ‘shocks’) in the crop, livestock, fisheries or aquaculture time-series and complimenting this with a qualitative analysis of probable drivers, this chapter illustrates how shocks can affect multiple food production sectors across land and sea. I show that shock events can displace human resource use from one sector to another or more commonly pose linked threats to food production across multiple sectors, hindering livelihoods adaptation, food security and driving changes in biodiversity. This chapter was published in *Nature Sustainability* in 2019.

Chapter 5 highlights the capacity for changing consumption patterns to shift human resource pressure between land and sea. By synthesizing data and comparing trends in Australian meat and fish consumption, I show that demands for animal protein are increasingly shifting dependence onto aquatic systems. As a result, consumption is increasing faster than domestic production can follow and the shortfall in this demand largely being met through imports from countries with poor governance over the social and environmental sustainability of seafood production. I show that despite poor public perceptions of aquaculture in the most important production regions in Australia, there is considerable potential for aquaculture growth to sustainably address land-sea shifts in consumption while reducing conflict around the coastal zone.

The thesis concludes with a summary of the findings of chapters two, three and four and five places them within in a discussion of greater need for food security research that works across typical epistemological borders and this thesis' contribution to that end. I conclude with a discussion of future directions in integrated land-sea food systems research and its urgency within wider sustainability considerations.

Chapter 2

2. Considering land-sea interactions and trade-offs for food and biodiversity

The research contained in this chapter has been published as:

Cottrell, R.S., Fleming, A., Fulton, E.A., Nash, K.L., Watson, R.A. and Blanchard, J.L., 2018. Considering land–sea interactions and trade‐offs for food and biodiversity. Global change biology, 24(2), pp.580-596.

See Appendix F for the PDF of this published article. It is presented here in its published form but formatted for the purpose of this thesis.

2.1. Abstract

With the human population expected to near 10 billion by 2050, and diets shifting towards greater per-capita consumption of animal protein, meeting future food demands will place ever-growing burdens on natural resources and those dependent on them. Solutions proposed to increase the sustainability of agriculture, aquaculture, and capture fisheries have typically approached development from single sector perspectives. Recent work highlights the importance of recognising links among food sectors, and the challenge cross-sector dependencies create for sustainable food production. Yet without understanding the full suite of interactions between food systems on land and sea, development in one sector may result in unanticipated trade-offs in another. We review the interactions between terrestrial and aquatic food systems. We show that most of the studied land–sea interactions fall into at least one of four categories: ecosystem connectivity, feed interdependencies, livelihood interactions, and climate feedback. Critically, these interactions modify nutrient flows, and the partitioning of natural resource use between land and sea, amid a backdrop of climate variability and change that reaches across all sectors. Addressing counter-productive trade-offs resulting from land-sea links will require simultaneous improvements in food production and consumption efficiency, while creating more sustainable feed products for fish and livestock. Food security research and policy also needs to better integrate aquatic and terrestrial production to anticipate how cross-sector interactions could transmit change across ecosystem and governance boundaries into the future.

2.2. Introduction

Population growth and dietary shifts towards greater consumption of animal-protein are expected to increase current human food demand by over 50% in the next 30 years (Alexandratos & Bruinsma 2012, Tilman & Clark 2014). Meeting these demands through further intensification and expansion of terrestrial, freshwater, and marine food production threatens global biodiversity and the structure and function of natural ecosystems (Brussaard et al. 2010). Creeping loss of environmental services from natural habitat destruction undermines the integrity of the human and natural components of our food system (Ostrom 2009), and poses a huge threat to the food security of millions of people. Thus, there is an urgent need to understand the social-ecological trade-offs from a variety of development pathways proposed to meet future food demands.

Meeting future consumption demands will require development across all food production sectors. On land, genetic modification, increased waste efficiency, or integrated pest management strategies can close the gap between realized and maximum potential crop yields (Godfray, Beddington, et al. 2010, Godfray & Garnett 2014, Tilman et al. 2011). Better fisheries management throughout the global ocean, and advances in aquaculture feed technologies may also allow per-capita fish consumption to increase, while reducing impacts on aquatic resources (Béné, Barange, Subasinghe, Pinstrup-Andersen, Merino, GI Hemre, et al. 2015, FAO 2016, Jennings et al. 2016). Yet, the challenge is not isolated to increasing production alone. Improving food security for 800 million people living in hunger worldwide requires tackling barriers to food access (Sen 1981). Overcoming disparities in access requires vast improvements in gender equity, trade reforms, and natural resource management as highlighted by the United Nations Sustainable Development Goals (FAO IFAD WFP 2015, United Nations 2015a). Most solutions, however, continue to focus on a combination of single sector approaches to development – including both aquatic and terrestrial food systems – but largely ignore the human dependencies that reach across multiple sectors and ecosystems.

Interactions among species or functional groups within ecological food webs are widely recognised as fundamental in determining system-wide responses to perturbations (Marzloff et al. 2016, Suttle et al. 2007). Here we apply the same thinking to an integrated global food system, with interacting marine, freshwater, and terrestrial sectors (fisheries, aquaculture, and agriculture) burdened by population growth, shifting diets, and climate change. Interactions among food sectors have pivotal roles in the transfer of impacts from one region to another via the disruption of environmental services and trade, or from human adaptation strategies that shift resource use (Warren 2011). Interactions between fisheries and aquaculture in the marine environment have been the focus of a substantial body of research in recent years (e.g. Naylor et al. 2000, Arechavala-Lopez et al. 2013, Natale et al. 2013). Nevertheless, the links and interactions spanning food systems and ecosystems on land and sea remain vastly understudied.

Lack of integration is not surprising given organizational and institutional norms, structures, and incentives that lend to specialised knowledge within disciplines (Viseu 2015), thus silo approaches to management. Nonetheless, we need a new perspective on sustainable development of the food system that incorporates how development in one sector can affect another. Recent work highlights how links and interdependencies connecting food sectors on land and sea present challenges for sustainable food production (Blanchard et al. 2017). Yet, the full scope of land-sea interactions among food production systems is not understood. To address this gap, we review the suite of interactions connecting terrestrial and aquatic (both marine and freshwater) production systems to highlight connectivity, and discuss the social-ecological trade-offs that result from various intensification strategies (see Appendix A ‘Chapter 2 Supplementary Information’ for review methods). We show that four main pathways link food sectors on land and sea: ecosystem connectivity, feed interdependencies, livelihood interactions, and climate feedback (Figure 2).

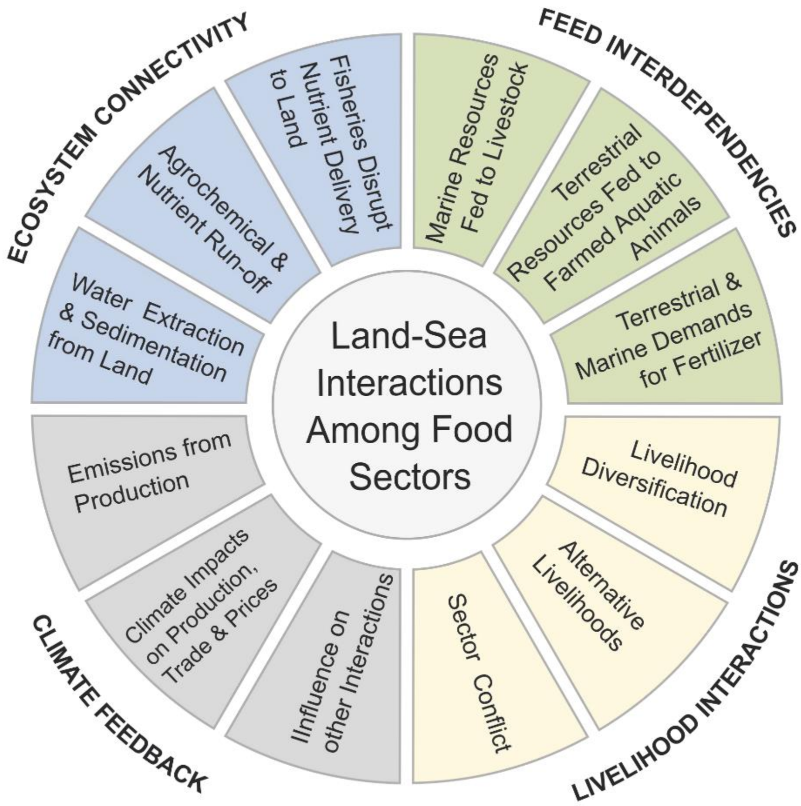

Figure 2 – Summary of Land-Sea Interactions among Food Production Systems. Ecosystem connectivity, feed interdependencies, livelihood interactions, and climate feedback link aquatic and terrestrial production systems.

2.3. Ecosystem Connectivity

Terrestrial, freshwater, and marine habitats are inextricably linked through the energy, material, or organisms that pass between them (Gorman et al. 2009). Rivers and streams play a fundamental role in the flow of subsidies across the land-sea interface (Tallis et al. 2008) and are pivotal in transferring impacts between systems. The asymmetric flow of water from land to sea means changes in habitat structure on land may be of greater consequence for aquatic systems than vice versa (Álvarez-Romero et al. 2011).

Water extraction for agriculture can pose significant threats to ecosystems and human activity downstream (Atapattu & Kodituwakku 2009). Agriculture accounted for 92% of global freshwater consumption from 1992-2005, primarily through irrigation (Hoekstra & Mekonnen 2012). Upstream water extraction and irrigation schemes reduce water flow otherwise delivered to coastal ecosystems with considerable impact on downstream fisheries. Reductions in lateral flooding and increases in salt-water intrusion limit the capacity for wetlands to support both biodiversity and productive fisheries, and has been a major source of conflict in deltaic areas in Asia, Africa, and Australia (Craig et al. 2004, Islam & Gnauck 2008, Lemly et al. 2000).

Terrestrial farming also influences the structure and function of aquatic systems worldwide through major changes to land-use. Conversions of forests, grasslands or wetlands to grazing or arable land are the most common (Galloway et al. 2010). Changes in vegetative-cover influence hydrological processes such as infiltration, which if decreased, increases surface-run-off and disrupts vegetative nutrient uptake (Galloway et al. 2010).

Hydrological alteration and changes to nutrient loading by crop-livestock systems are the single largest source of disruption to nitrogen and phosphorous flows between ecosystems (Bouwman et al. 2013). Global, regional and local transfers of nitrogen have undergone dramatic transition since the Haber-Bosch process allowed humans to convert non-reactive nitrogen gas to ammonia for use in synthetic fertilisers (Galloway et al. 2003, Galloway et al. 2010). Globally, crop systems receive 75% of all reactive nitrogen compounds created by humans. The vast majority of fertilisers applied are lost to waterways and the atmosphere – only 20% of nitrogen delivered to arable land reaches livestock, less than 10% directly contributes to human food. Moreover, on a global basis approximately 85% of nitrogen fed to cattle is lost in manure and waste (Galloway et al. 2003, Galloway et al. 2010, Smil 2002). Manure stored in earthen ponds then leach massive quantities of nutrients into groundwater and waterways, exacerbating nitrogen deposition in aquatic environments (Kato et al. 2009, Tilman et al. 2002).

Diffusing into rivers and streams, agricultural run-off is a major driver of biodiversity loss in aquatic habitats worldwide. Inputs of sediment and nutrients act synergistically, leading to reductions in water quality, and alterations to deposition and flow in adjacent freshwater environments (Dudgeon et al. 2006). In Europe and North America, smothering of fish nests or 'redds' can also affect the recruitment of commercially important anadromous fish such as salmon (Heaney et al. 2001).

Anthropogenically mobilized nitrogen and phosphorous in aquatic environments make their way downstream to coastal waters and are a substantial source of inshore nutrient enrichment (Howarth & Paerl 2008). Marine habitats can become eutrophic as aquatic plants flourish from nutrient enrichment and subsequently die, depleting dissolved oxygen concentrations in bottom waters (Rabalais 2002). Low oxygen availability (hypoxia) effectively compresses suitable habitat for foraging and reproduction in marine species, increasing local mortality (Breitburg 2002). This may be exacerbated in coastal systems that naturally experience significant stratification, and where subsequently, oxygenated and oxygen-deficient water bodies are not able to mix, isolating benthic organisms in hypoxic environments (Diaz & Rosenberg 2008). Nutrient-driven hypoxia that persists can produce large areas devoid of marine life known as 'dead zones', significantly reducing fisheries catch (Diaz & Rosenberg 1995, Renaud 1986). Over 400 dead zones exist in coastal areas worldwide, many of which are in major fishing grounds such as the Baltic Sea, East China Sea, and the Gulf of Mexico (Diaz & Rosenberg, 2008). As fish and invertebrates die and decay, they not only cause further draw down of oxygen (creating positive feedback conditions), but huge biomass potential is lost from fisheries; estimates place this loss as high as 734 000 T C yr^{-1} over an area of 245 000 km2 (Diaz & Rosenberg, 2008).

Diffusion of herbicides from land into coastal aquatic environments are of additional concern given their inhibiting effect on photosynthetic productivity – a threat to phytoplankton, mangroves, seagrasses, sponge, and coral symbionts (Kennedy et al. 2012). Herbicides used in sugarcane plantations in northeast Australian river catchments have been linked to widespread coastal mangrove dieback, and so the degradation of fish nursery habitat (Duke et al. 2005). Reductions in coral or coralline algae growth rates from chronic exposure to sub-lethal herbicide concentrations also present an additive stressor affecting marine ecosystem function and services (Lewis et al. 2012).

While the flow of subsidies typically moves from land to sea, interactions are not always unidirectional. For instance, anadromous fish are important conduits of sea to land connectivity. Foraging in the ocean and dying in freshwater breeding grounds, they are important vessels of nutrient transfer between marine and terrestrial ecosystems (Gende et al. 2002). Fishing operations harvesting fish before they return inland may alter the flow of nutrients to the terrestrial ecosystems that support food production (Álvarez-Romero et al. 2011).

Management challenges on the Great Barrier Reef exemplify the consequences of ignoring ecosystem connectivity between land and sea. Despite the reef-zoning plan introduced in 2004, coral reef quality has continued to decline in central and southern reef regions in recent years (GBRMPA 2014). A major contributor to this decline is poor water quality caused by dissolved inorganic nutrient run-off from river catchments outside of the Great Barrier Reef Marine Park (GBRMPA 2014). Agricultural fertilisers, largely derived from intensive sugarcane production and horticulture in the Great Barrier Reef catchment are by far the largest nutrient source (GBRMPA 2014, Waterhouse et al. 2015).

Nutrient enrichment is also a hypothesis for a potential cause of increased larval survival of the Crown of Thorns Starfish (Acanthaster planci) (Wooldridge & Brodie 2015)., This large corallivorous starfish was responsible for over 40% of coral reef loss on the Great Barrier Reef between 1985-2012 (De'ath et al. 2012). These downward trends in coral reef cover and habitat complexity, parallel steady decreases in catch per unit effort in both recreational and commercial reef fisheries (GBRMPA 2014). Notwithstanding continued investment into improved land management practices by governments, regional management bodies, and landowners, land-based run-off still presents one of the greatest threats to the Great Barrier Reef (GBRMPA 2014).

As food demands grow, the influence of agricultural run-off to freshwater and marine environments across the globe is of great concern. Fertilizer consumption continues to rise in the majority of countries to support crop production (Figure 3) and this trend is likely to persist. Cereal production alone will need to increase by one billion tonnes (from an early 2000s baseline) to meet 2050 food demands (Alexandratos & Bruinsma 2012). At present, animal feeds consume over 30% of crops grown and with a shift away from grazing to feed-dependent livestock systems, total fertiliser demand drawn from meat products is set to rise (Alexandratos & Bruinsma 2012). Moreover, supplying greater demand for livestock products will directly contribute to increases in nutrient loading on land from manure. Global nitrogen and phosphorous wastes generated by livestock effluent already exceed that of fertiliser use (Bouwman et al. 2013). Thus, trends in human diets will be a major determinant of land-sea nutrient flow into the future. Consumption of animal-based protein is inherently inefficient in the transfer of nutrients from fertilizers to humans. Continued global trends towards current western diet portfolios will exacerbate regional surpluses of nitrogen and phosphorous in agricultural soils (Bouwman et al. 2013). Replacement of beef with poultry and pork and more plant-based diets, however, may prove effective in reducing these surpluses and the costs of terrestrial production for aquatic systems (Bouwman et al. 2013, Galloway et al. 2010).

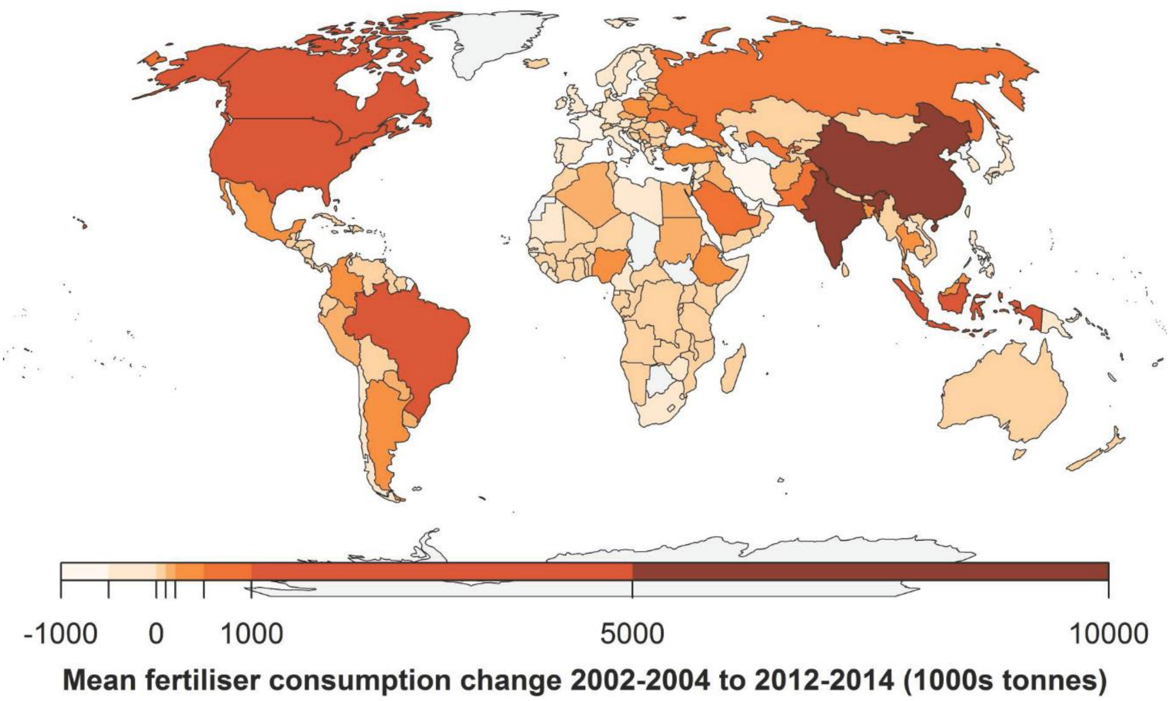

Figure *3* – Global ten-year mean change in synthetic fertilizer consumption. Mean change in consumption calculated from differences in average nitrogen and phosphorus fertiliser consumption between 2002 – 2004 and 2012 – 2014 (scale in 1000s of tonnes). Total annual consumption equals domestic production plus imports minus exports. Grey shading represents countries with incomplete or no data for fertilizer consumption from 2002 – 2014. Data sourced from the Food and Agriculture Organization (FAO) of the United Nations (FAO 2019a).

In low-latitude countries, vulnerability to coastal enrichment is compounded, not just by pollution exposure, but the susceptibility of nitrogen-deficient tropical waters to eutrophication, and the high human dependence on fisheries for food security (Beman et al. 2005). The implications of cross-system connectivity also extend beyond coastal waters and into management considerations for offshore marine areas. There is evidence to suggest that closure of open ocean areas (outside of exclusive economic zones) could result in greater fisheries yields (White & Costello 2014) or at least reduced inequalities in fisheries distribution at a global level (Sumaila et al. 2015).This is, however, contingent on coastal waters remaining productive in the face of greater agricultural run-off potential. Thus, fisheries governance needs to consider terrestrial influences on marine production and vice versa. While this is beginning to be recognised in Integrated Land-Sea Management plans that cover catchment to coastal ecosystems, examples of successful implementation are rare (Reuter et al. 2016).

2.4. Feed Interdependencies

Urbanisation and increased affluence are shifting human diets to greater proportion of animal-based protein. In 2009, the 15 wealthiest nations consumed 750% more ruminant, seafood, poultry, and pork meat per capita than the poorest 24 nations (Tilman & Clark 2014). With growing demand for both terrestrial livestock and cultured aquatic organisms, the supply of feed must also keep pace (Boland et al. 2013, Tacon & Metian 2015). Sourcing feed for livestock and fish production also increases inter-dependencies among food systems on land and sea (Blanchard et al. 2017, Troell, Naylor, et al. 2014).

Historically, both agriculture and aquaculture have depended on fishmeal and fish oil as important constituents of animal feeds. Fishmeal and oil are primarily sourced from small pelagic, or ‘forage’ fish, caught and processed for non-food purposes (Fréon et al. 2014, Tacon & Metian 2009) and are a valuable source of high grade protein and long-chain, polyunsaturated fatty acids for domesticated animals (Stoner et al. 1990). Nonetheless, dependence on fishmeal and oil inputs for animal feed has come under question as meat and fish production grows to meet consumer demand. Large-scale harvesting of small pelagic fish is implicated in the decline of several higher trophic level fish stocks, disrupting energy flow in marine food webs by removing key prey species for a range of organisms

(Naylor et al. 2000b). It has also sparked debate about the use of marine resources as animal feed rather than for human food (Allison 2011, Tacon & Metian 2009, Wijkstrom 2009).

To improve sustainability, and in response to rising fishmeal prices (Tacon & Metian 2008), aquaculture is increasingly replacing marine ingredients with terrestrial proteins and oils in feed (Troell, Naylor, et al. 2014). Indeed, aquaculture demand for fish products has not grown in 20 years despite the many fold increase in production (Tacon et al. 2011). This is due to an increase in aquaculture efficiency, but also because crop products (such as soybean and maize) and by-products of livestock production (meat and bone meal) are increasingly used as fishmeal substitutes (Watanabe 2002). Despite the nutritional challenges of increasing vegetable products in fish diets, (Brinker & Reiter 2011, Midtbo et al. 2015), technological progress has been rapid and some feed manufacturers now supply fishmeal-free aqua-feeds (Skretting 2015, Skretting Australia 2016). Fish-oil remains necessary within the feed of many carnivorous fish for now, but new research highlights the potential for substitution by marine algae (Sprague et al. 2015).

Aquaculture remains the largest consumer of fishmeal and oil (Tacon et al. 2011), but greater inclusion of crop-based ingredients in feeds means the terrestrial costs of aquatic production are also increasing. Feed crops and expansion of inland production is increasing aquaculture's reliance and pressure on freshwater resources (Jessica A Gephart et al. 2017). Aquaculture's environmental impacts may now include agricultural run-off (Fry et al. 2016) and estimates placed global freshwater use between 31-39 km3 in 2008 (Pahlow et al. 2015). For the same year, Fry et al. estimate the land area required to grow the top five aquaculture feed crops (soybean, rapeseed, maize, groundnuts and wheat) was comparable to the size of Iceland (Fry et al. 2016).

Land is already a scarce commodity and becoming increasingly so across many nations of the world as croplands, pastures, biofuel feed stocks, urban areas, protected natural areas, and forestry plantations continue to expand (Lambin & Meyfroidt 2011). While some activities are displaced into ocean areas (e.g. energy production), pressure on land use from food production, including aquaculture production will continue. There is great dependence on terrestrial livestock to supply increased meat demands globally (Naylor et al. 2005), but the growth of inland pond aquaculture – the largest source of farmed fish – may increase conflicts for space (Edwards 2015, FAO 2016). Aquaculture continues to outstrip the growth rate of other production sectors (Figure 4a), and while increasing competition for freshwater and land is pushing some forms of aquaculture further out in the marine space, this is not consistent everywhere (Troell, Naylor, et al. 2014). In areas where suitable coastal sites are unavailable or transition costs are too great, inland aquaculture is expanding into agricultural land. With competition for production space and feed crops, conflict between terrestrial and aquatic food systems has the potential to increase (Troell et al. 2014). This may be of particular concern in several Asian countries, which account for the majority of global inland aquaculture (Figure 4b), and where rapid population growth and urbanisation create further constraints on land use (United Nations 2014, United Nations 2015b).

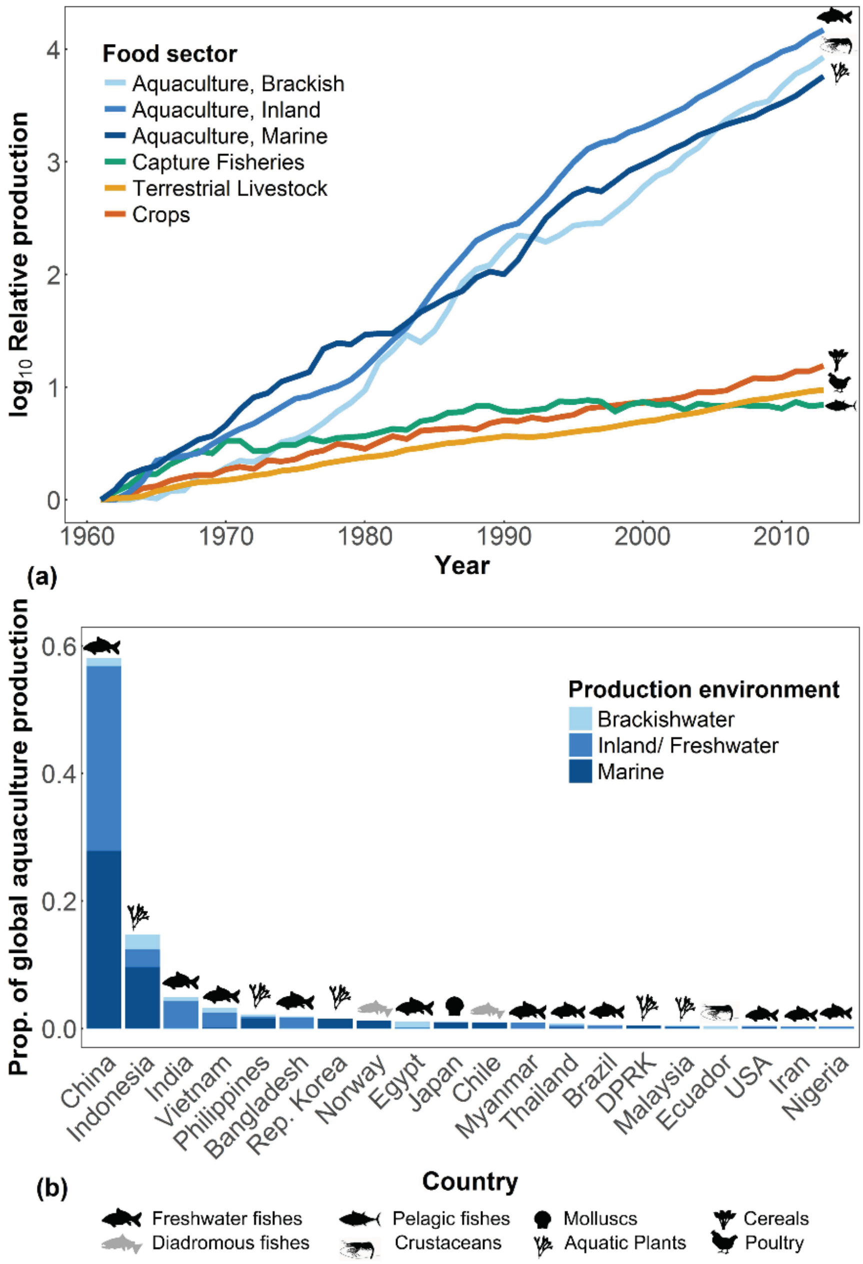

Figure 4 – Cross-sector and spatial comparisons of global aquaculture growth and production. (a) Log-relative change in total aquaculture (inland, brackish and marine), terrestrial livestock, crop, and capture fisheries production from 1961 – 2013. Image symbols represent functional groups responsible for greatest absolute change (tonnes) within sector over time-period **(b)** Proportion of global aquaculture production from top 20 producing nations (>95% of global production by weight) by culture environment in 2015. Image symbols represent largest functional group contributions to domestic production (tonnage) in

2015. Aggregate livestock, crop, and aquaculture commodity data sourced from the FAO (FAO 2019a, FAO 2019b) and capture fisheries data taken from Watson (2017).

Understanding the trade-offs between expansion/intensification of inland fish production and land used for agricultural purposes will be important as food demands rise (Edwards 2015). Improving freshwater use efficiency in aquaculture will also need consideration as water scarcity increases (Edwards 2015). Thus, there is a pressing need to establish how to best use current cultivated land for multiple pathways of food production. Greater conflict among sectors for land, water, and energy may disproportionately affect the food security of people in developing countries. The majority of non-cultivated land suitable for cropping is found in Latin America and Sub-Saharan Africa where a heavy burden of hunger and poverty already exists, and land and water-acquisition by foreign governments further redirects resources away from local markets into exported goods (Lambin & Meyfroidt 2011, Rulli et al. 2012).

Feed interdependencies continue to shift impacts of animal production in the opposite direction too. Pigs and poultry accounted for 20% and 5% of global fishmeal consumption respectively in 2010 (Shepherd & Jackson 2013). While this proportion is significantly lower than fifty years ago, the pork industry's share of consumption has stayed relatively stable since the late 1980s (Tveterås & Tveterås 2010). Lower vulnerability of the pork industry to fishmeal price increases is likely due to the disproportionately beneficial effect that even small fishmeal feed inclusions have on the growth rates of early-weaned piglets (Tveterås & Tveterås 2010). Thus despite price increases, inclusion of fish inputs in specialty and starter feeds for terrestrial livestock are likely to persist into the future (Kristofersson & Anderson 2006).

Maintaining and increasing crop production for feed and food is entirely dependent on access to phosphorous for fertilizer production (Neset & Cordell 2012). Traditionally, manure, bone meal, and even human excreta were used to supply soils with phosphorous

(Cordell et al. 2009). During the 19th century, significant deposits of seabird guano were mined on Pacific Islands and started to replace local phosphorous sources (Cordell et al. 2009), providing some of the earliest land-sea interdependencies in food production. Although, it was the discovery of phosphate rock sources on land that transformed fertilizer industries. These highly concentrated rock-derived nutrients were key to substantially increasing yields during the Green Revolution (Cordell et al. 2009).

Mineral phosphate sources are, however, a finite resource, with phosphate production expected to reach its peak at some point this century (Neset & Cordell 2012). Now there is potential for the impacts of phosphate mining to spill over into the marine environment. Growing food demands require greater fertilizer supply, and phosphate deposits in margin sediments are currently being targeted for exploration off Namibia, New Zealand, and Mexico (Mengerink et al. 2014). The impacts of these dredging operations to benthic environments and fisheries are of great concern and uncertainty (Mengerink et al. 2014), and provide another example of how production demands in one sector may produce trade-offs in another.

Interdependencies among sectors do not exist or act in isolation, but also interact with the natural ecosystem connectivity mentioned in the previous section. In an ever-globalizing world, demands for animal feed now drive ecosystem change in areas distantly removed from animal production (Liu et al. 2013, Österblom et al. 2016). Production pollution, trade, processing, use, and the subsequent waste of feed products redistributes the flow of energy, nutrients, and organisms between aquatic and terrestrial ecosystems at macroecological scales (Figure 5).

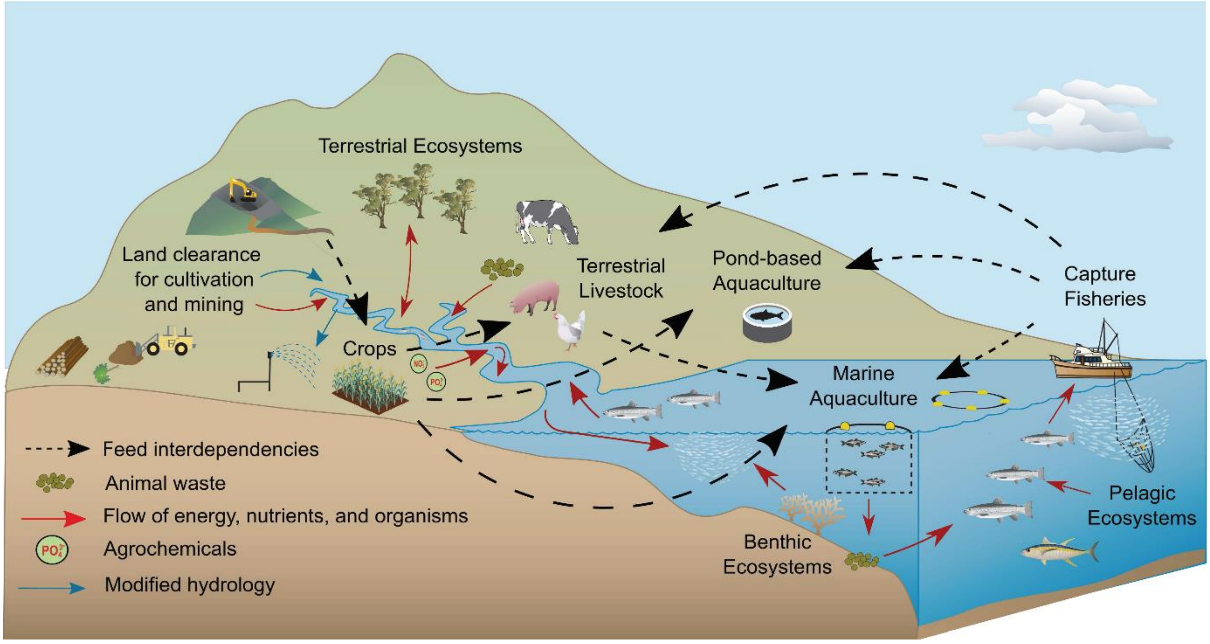

Figure 5 – Feed interdependencies redistribute land-sea nutrient flows over large spatial scales. Run-off from land-clearance and agricultural nutrient waste influences the productivity of coastal waters globally, while fisheries may disrupt the flow of nutrients to terrestrial ecosystems. The trade, use, and waste of livestock and aquaculture feeds redistribute nutrients between land and sea, often over vast distances. Intensified use of feed products then contributes to aquatic and terrestrial nutrient surpluses, interacting with natural land-sea connectivity.

Ultimately, sustainable food system development needs to consider inefficiencies associated with feeding a growing global population with greater proportions of animal-based protein. For example, Foley et al. (2011)calculate that an extra one billion tonnes of crop-based human food could be supplied by redirecting total production of 16 major crops away from animal feed. Merino et al. (2012) estimated that aquaculture's high dependence on forage fish for feed could limit the capacity of aquatic production systems (cultured and wild caught) to meet seafood demands projected by 2050. Continued growth in the aquaculture sector will require either a greater market share in fishmeal and oil consumption or even further movement away from marine feeds to prevent ecological collapse in marine systems (Merino et al. 2012). But as aquaculture transitions to more crop-based feeds, food production pressures on land grow, increasing inter-sectoral conflict for resources, or further threatening terrestrial ecosystems through the expansion of (Foley et al. 2011, Mayaux et al. 2005, Newbold et al. 2015). Furthermore, relative contributions from pigs and poultry to total livestock production are increasing (Davis et al. 2015). Whether these shifts pose a threat to marine systems through demands for fishmeal will likely depend on the meat industry's flexibility to switch feed ingredients under changing environmental and market conditions.

Advances in feed technology could play an important role in increasing the sustainability of future food production. Both insects and algae show potential as a source of protein and fatty acids for livestock as at least partial replacement for fishmeal and oil (van Huis 2011, Angell et al. 2016). Both can be produced intensively within warehouses, fed by organic side streams, reducing land and water footprints of production (Sanchez-Muros et al. 2014). Seaweed products have also demonstrated their potential as a replacement for conventional crop fertilizers (Cole et al. 2016). To what extent these novel products can substitute the aquatic and terrestrial resources currently used remains unclear, as does any unintended consequences of their use, but with current trends in diets it seems likely cross-sector feed interdependencies will persist in one form or another into the future.

2.5. Livelihood Interactions

Resource partitioning of human livelihoods also link terrestrial, freshwater, and marine food systems across the globe. Mixed-farming methods, common throughout Asia, simultaneously integrate fish production into agricultural systems. Waste from one sub-system of fish, cattle, or crop production is used as a nutrient or feed input for another (Ahmed et al. 2014); reducing the need for off-farm labour, synthetic fertilizers and feed, improving household and resource efficiency (Begum et al. 2015, Blythe 2013, Prein 2002).

Livelihood diversification between terrestrial and aquatic systems may also compensate for seasonal changes to resource availability (Cinner et al. 2012). Supplementing terrestrial farming with aquatic production (and vice versa) at different times of year is a coping strategy documented across Asia, Africa, the Pacific Islands, and the Caribbean (Allison & Ellis 2001, Fisher et al. 2017). For economies dependent on African inland fisheries for example, people fish lakes and waterways when they are in flood, then cultivate land exposed by receding floodwaters in the dry season (Sarch 1996). In Indonesia, switches between rice or tree-crop farming and fishing are common in response to fish availability (Allison & Ellis 2001). Alternating activities between sectors in response to fluctuating resources, improves the stability of local food availability throughout the year. Income gained from one sector is invested back into another, protecting against social-ecological shocks (Allison & Horemans 2006, Cinner et al. 2012, Sarch 1996) but also linking aquatic and terrestrial sectors through their own productivity. The prevalence of such inter-sectoral dependence in human livelihoods is widespread. Recent analysis of demographic and household data from three continents reveals how coastal fisheries-dependent communities more commonly co-depend on terrestrial production than not (Fisher et al. 2017).

Human adaptation strategies that produce land-sea switches can, however, also serve as a compounding stressor on recipient sectors – shifting the pressures of human food provision to one system when resources in another fail. During times of poor coastal fish harvests, the coastal communities most affected may seek alternative livelihoods in bushmeat hunting or agriculture for income generation and sustenance (Brashares et al. 2004). Unsustainable wildlife harvesting may increase as deforestation for agricultural and timber production open up forests to hunters and the bushmeat trade (Houghton 2012). The reverse trend has occurred where poorly planned water development programs, resource-based corruption, or drought on land displaces nomadic pastoralists and farmers to the coastline (Collins 2016). Shifts from terrestrial systems that lead to unregulated increases in fishing capacity can exacerbate trends of declining catches, overexploiting marine resources in an effort to maintain income (Collins 2016, Pauly 1994). Erosion of resources and livelihood options like this are also a driver for maritime piracy, and a connection to wider clan-based crime networks (United Nations Security Council 2016). Understanding how changes to food production in different sectors will displace human resource use across ecosystem boundaries, will become increasingly important in a world where global change influences ecosystem services and food resources across multiple sectors on land and sea.

Where food intensification pathways fail to consider cross-system impacts on other sectors, subsequent shifts between agriculture and seafood production may be a source of significant social-ecological conflict and reduced food security. The rapid expansion of intensive shrimp aquaculture in Southeast Asia provides a prominent example. Producing luxury goods destined for growing developed world markets, shrimp farming represents considerable export potential for developing countries and is now the second largest aquaculture industry by value (FAO 2016). The profitability of shrimp production has led to rice farmers across Vietnam, Thailand, India and Bangladesh converting paddy fields into shrimp ponds to boost household income (Bhat & Bhatta 2004, Dung et al. 2009, Gowing et al. 2006). But the dramatic transition in resource use has also led to widespread conflicts among modern and traditional food producers in coastal Asia.

As aquaculture has expanded, mangrove areas are cleared and ponds extended landward (Figure 6a,b). Intrusion of salt water from shrimp ponds into adjoining agricultural land has salinized soil and groundwater in many areas, resulting in reduced grazing land and lowered crop productivity (Paul & Roskaft 2013, Paul & Vogl 2011). Clearance of mangrove forests for pond structures negatively influences local fisheries by reducing mangrove-associated stocks and blocking fishers access to the coast (Ahmed & Glaser 2016, Primavera 2006). Furthermore, mangrove deforestation places coastal communities at greater risk of flooding from storm events or sea-level rise (Ahmed & Glaser 2016) and reduces the availability of vegetative materials (such as fruits or herbs) originally farmed or collected from the mangrove forests themselves (Jusoff & Bin Hj Taha 2008).

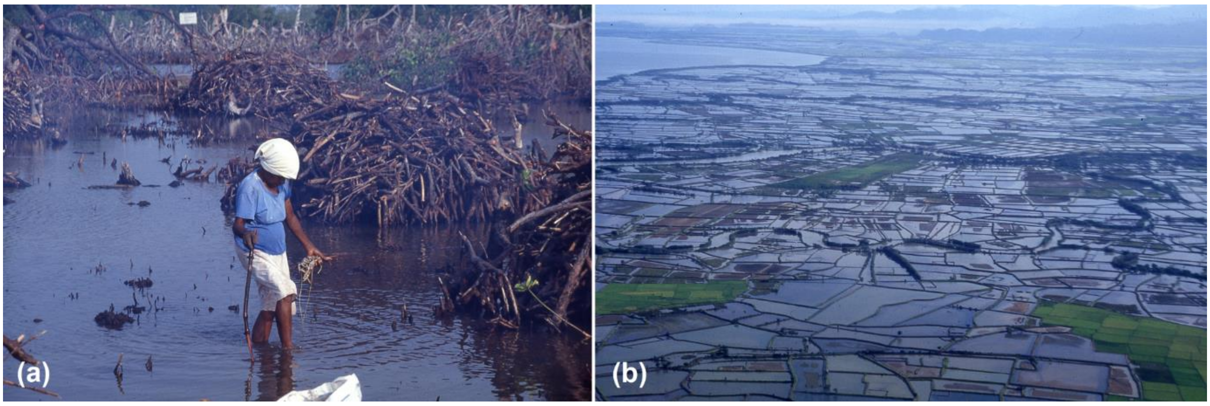

Figure 6 – Cross-sector livelihood conflicts. **(a)** Local fisher foraging after clearance of a mangrove forest for shrimp aquaculture development in Irian Jaya, Indonesia. **(b)** Expansive shrimp aquaculture located in former mangrove wetlands near Ujang Pandang, Sulawesi, Indonesia.

While more affluent individuals and families may be able to transition into shrimp cultivation, those rice farmers or fishers with lower household capital have few alternatives for income generation (Paul & Vogl 2011). As a result, many turn to felling mangrove vegetation to sell as firewood, worsening biodiversity loss, inter-sectoral conflict and the risk of coastal flooding and storm damage (Paul & Vogl 2011). Forceful displacement of traditional landowners has been reported in many areas and the less labour-intensive aquaculture rarely provides sufficient positions for alternative income (Gowing et al. 2006; Paul & Vogl 2011). Consequently, the surplus rural workforce are increasingly marginalized, becoming refugees of aquaculture expansion, and may be forced to migrate to cities, compounding the issue of urban poverty and food insecurity (Gowing et al. 2006).

Best management practices continue to improve resource-efficiency of shrimp farming (Paul & Vogl 2011) but the social-ecological complications surrounding these intensive systems provide a stark example of how meeting global food demands without considering cross-sector trade-offs can fundamentally undermine food security at local levels. Changes to, or diversification of human livelihoods discussed above, alter patterns of terrestrial and aquatic resource use through the temporal or spatial partitioning of food production activities. Development of food systems from single sector perspectives ignores cumulative and interactive ecosystem impacts acting across sectors and overlooks the effect of shifts in resource use onto other ecosystems arising from livelihood adaptation. Critically, this interplay among sectors is occurring against a backdrop of environmental variation and change. We use the social-ecological feedbacks produced from intensive shrimp farming as an example to illustrate the synergies between ecosystem connectivity, feed dependencies, livelihood interactions, and climate feedback (Figure 7).

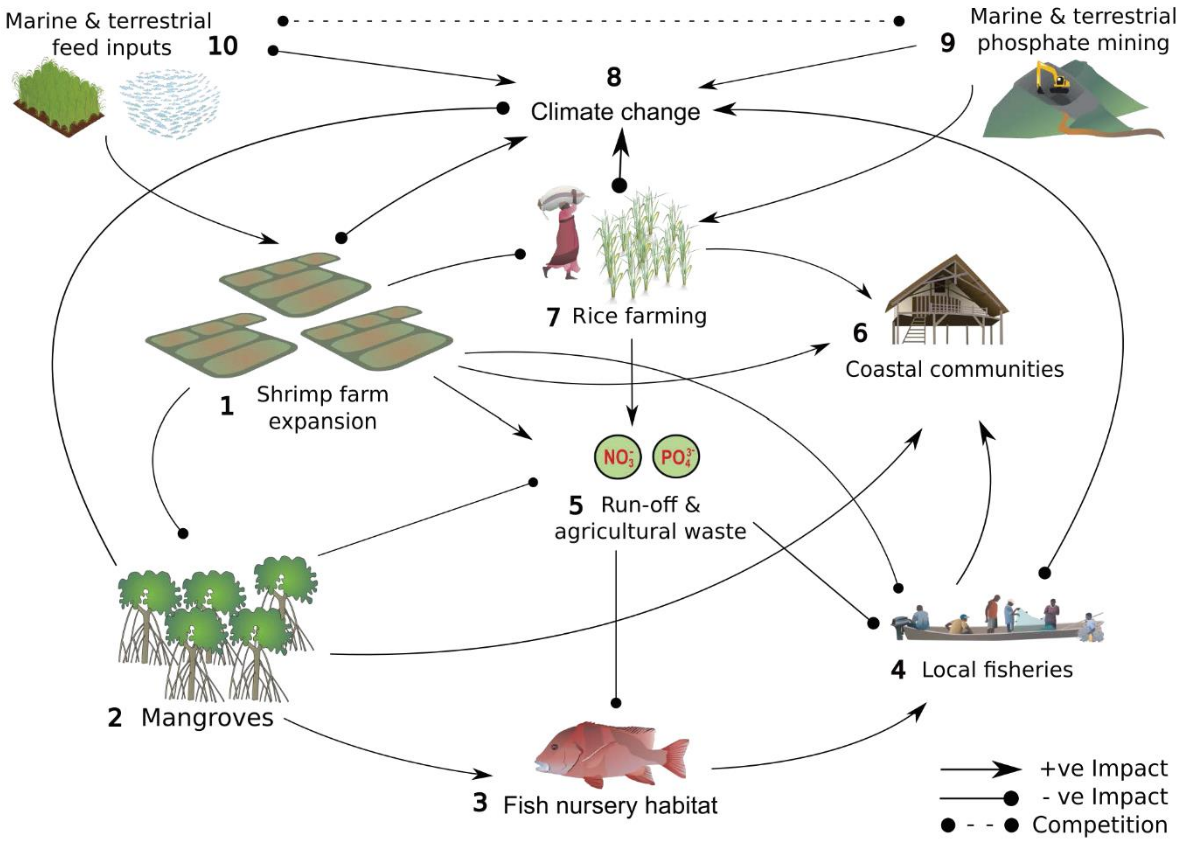

Figure 7 – Intensive Shrimp Farming as an example of complex social-ecological, land-sea interactions. Bracket numbers and arrows describe figure interaction pathways resulting from the expansion of shrimp farming (1). Livelihood benefits for adaptable households (1→6). Negative impacts on fisheries livelihoods from mangrove clearance (1→2→3→4→6 or 1→5→3→4→6 or 1→2→5→3→4→6), pollution (1→5→4→6), and reduced beach access (1→4→6). Negative impacts on rice farmer livelihoods from degraded soil and coercive displacement (1→7→6). Aquaculture, fisheries, and farming are impacted by climate change (8→1, 8→4, 8→7) but also emit greenhouse gases (1→8, 4→8, 7→8). Removal of mangrove forests reduces carbon storage (1→2→8) and increases risk of coastal flooding (1→2→6). Agriculture and aquaculture also rely on fertiliser (9→7) and feed inputs (10→1) which both contribute to climate change (9→8, 10→8) and compete for land, water and energy at macroecological scales (9→10).

2.6. Climate Feedback

Terrestrial and aquatic food sectors significantly contribute to greenhouse gas emissions, and are in turn impacted by climate change; providing further, albeit, indirect links between land and sea.

2.6.1. Emissions from Food Production

Food production contributes to carbon dioxide (CO2) emissions through the use of fuel-driven machinery and the processes of packaging, transportation and spoilage along the supply chain (Sonesson et al. 2010). Carbon dioxide is the primary emission from capture fisheries which are heavily dependent on fossil fuel for harvesting wild fish (Avadí & Fréon 2013, Tyedmers et al. 2005). But emissions differ considerably between size of vessels, gear types, and on board traditions (Basurko et al. 2013).

Primary agriculture and aquaculture greenhouse gases emissions originate from their production cycles and these vary greatly in quantity and form. Terrestrial agriculture acts as both a sink and a source of atmospheric CO2, but substantial emissions of methane and nitrous oxide are also produced, which hold greater global warming potential (Smith et al. 2014). Agriculture is the greatest contributor to non-CO2 emissions globally (Smith et al. 2014); methane produced by cattle rumination is the single greatest source (Sonesson et al. 2010). Although, novel feed ingredients, such as seaweed, show promise for reducing methane production (Maia et al. 2016). Outside of the production cycle, land clearing is also responsible for huge releases of CO2 and contributes to warming via alterations to the albedo of the Earth’s surface (Myhre et al. 2013, Smith et al. 2014).

Only recently has attention focussed on emissions from aquaculture production. Dissolved ammonia and ammonium are generated in aquaculture systems from faeces and waste feed (Hu et al. 2012). These are converted to nitrate and then into nitrogen and nitrous oxides by nitrifying and denitrifying bacteria respectively (Hu et al. 2012). The quantity of emissions produced by a given operation depends on methods of nitrogenous waste disposal, feeding rate, water pH, salinity and oxygenation (Hu et al. 2012), but conservative estimates suggest aquaculture currently produces ~4% of agricultural emissions (Williams & Crutzen 2010). With the current growth rate of aquaculture, this could rise to 20% by 2030, particularly as a switch to plant-based feeds may increase nitrous oxide emissions from the crop-growing phase (Williams & Crutzen 2010).

2.6.2. Climate Change Consequences for Terrestrial and Aquatic Food Systems

Climate change influences food systems on both land and sea. On land, changes to temperature, precipitation and CO2 concentrations influence crop growth rates, the duration of growing seasons, water availability, soil moisture, viability of grazing pastures, and the frequency of storm events (Calzadilla et al. 2013). While in the oceans, warming and acidification drive changes to marine species survival, distribution, and reproduction by influencing a number of biotic and abiotic factors. Warmer, more acidic water alters patterns in salinity, circulation, stratification, storm event frequency, and ecosystem structure; and influences metabolic function and behaviour of many vertebrates and invertebrates (Doney et al. 2009, Laffoley & Baxter 2016, Messmer et al. 2016, Rhein et al. 2013, Rummer & Munday 2017).

Global agricultural production is expected to decrease by 2-3% over the next 30 years due to climate change, leading to reductions in human welfare of over USD $300 billion (Calzadilla et al. 2013). Impacts will vary spatially. Warmer temperatures, greater precipitation, and carbon fertilization may benefit crop yields in higher latitudes, through shorter frost periods and increased water availability (Rosenzweig et al. 2014). In contrast, even moderate temperature increases in low latitudes are expected to decrease crop yields by lowering water availability for rain-fed systems and reducing soil moisture (Calzadilla et al. 2013; Rosenzweig et al. 2014).

The effects of climate change on fisheries will also differ geographically. As a response to warming, marine species continue to track preferred temperature conditions, migrating offshore and pole-wards to cooler waters (Allison & Bassett, 2015; Pecl et al., 2014). Species shifts such as these are expected to redistribute global catch potentials, decreasing the productivity of tropical fisheries in particular, and increasing catch in temperate regions (Barange et al. 2014, Cheung et al. 2013, Pecl et al. 2014). Although, the catch of fleets from high latitude countries operating in foreign tropical waters are also likely to sustain losses (Lam et al. 2016). Latitudinal shifts are of great concern for inland fisheries too, where redistributions within freshwater systems may cross national borders (Ficke et al. 2007). The inability for some species to track thermal gradients in east-west orientated systems may also lead to changes in fisheries structure as more thermal tolerant species prevail (Ficke et al. 2007), with unknown consequences for local economy, ecology, and human well-being.

Despite latitudinal trends, patterns of climate change impacts vary across similar latitudes on land or in the ocean; instead particular hotspots are expected. Tropical South America, South Asia and some areas of Africa (such as the Ethiopian highlands) are all expected to experience reductions in agricultural productivity over the coming decades (Piontek et al. 2014). Further, these declines will likely be experienced in combination with other cumulative stressors such as water scarcity and ecosystem degradation (Piontek et al. 2014). Twenty-four hotspots of rapidly warming areas in the global ocean have also been identified, and the majority are found in tropical regions (Hobday & Pecl 2014). Of particular concern are areas projected to experience simultaneous reductions in fisheries and agricultural productivity under climate change. While some European countries (e.g. Norway and the UK) may experience such double jeopardies, simultaneous land-sea impacts are likely to disproportionately affect people in developing nations of low adaptive capacity, high population growth, and heavy hunger burdens (Blanchard et al. 2017).

Aquaculture may be the exception to the trend of a widening production gap between high and low latitude countries. The temperature changes expected in the tropics are within the optimal ranges for most cultured species and warmer waters may increase feed utilization efficiency and growth rates in marine, freshwater and brackish production (De Silva & Soto 2009). In contrast, aquaculture in higher latitudes is more vulnerable to warming. For example, the huge salmon industry relies on a narrow temperature band for optimum fish growth (Bell et al. 2016). Relocation of salmon farms is already happening in response in southern Tasmania, Australia. Potential resilience of tropical aquaculture could provide a solution for countries experiencing the greatest reduction in fisheries and agriculture, although at present, only a handful of countries account for the majority of aquaculture production (Figure 4b). Expanding aquaculture in countries that need to counteract decreases in other food sectors will require coherent policy developments that encapsulate a wide range of interacting economic, social, and environmental factors (Beveridge et al. 2010).

Beyond food availability, climate change will also impact food access, stability and utilization into the future (Wheeler & von Braun 2013). Variability of crop production can influence food prices and thus purchasing access or income from food production (Nelson et al. 2014). In fisheries, biogeographical distribution shifts can affect operational costs, economic rents and fish prices (Sumaila et al. 2011). Changes to production also influence international trade. Russia, South Asia and the Middle East are likely to see reductions in welfare arising from lower competitiveness of agricultural product. In contrast, sub-Saharan Africa, China and northern South America may see their relative trade position improve (Calzadilla et al. 2013). These effects may also be occurring against a background of changing disease pressure on agriculture and aquaculture systems (Bell et al. 2016; Wheeler & von Braun 2013) and greater instability of production brought about by increased climate variability (Wheeler & von Braun 2013). Food security in the most threatened regions is further threatened as people become displaced or impoverished by more frequent extreme weather events, sea-level rise, water scarcity (Gemenne 2011).

Finally, climate change is also likely to influence the land-sea interactions discussed here. Changes to precipitation regimes and extreme weather events expected will alter hydrology, dictate the need for fertiliser and pesticide applications, and determine to what extent agricultural nutrients can influence aquatic environments. Climate-induced changes to the availability, accessibility, stability, and safety of crop and livestock resources, including any influence on trade, will affect both the quantity and quality of both marine and terrestrially sourced feed products. Spatial shifts in marine or terrestrial production will also have implications for the livelihoods of people in the recipient and vacated regions with, as yet, unknown effects.

2.7. Bridging the Land-Sea Divide: Progress, Challenges and Solutions

We have shown that the nexus of ecosystems, feed production, human livelihoods and climate fundamentally link food systems on land and sea (Figure 8). Yet integration of aquatic and terrestrial components in food security research and policy is lacking. Accounting for, and where possible, addressing land-sea interactions will provide a crucial mechanism for preventing unintended outcomes from food system development.

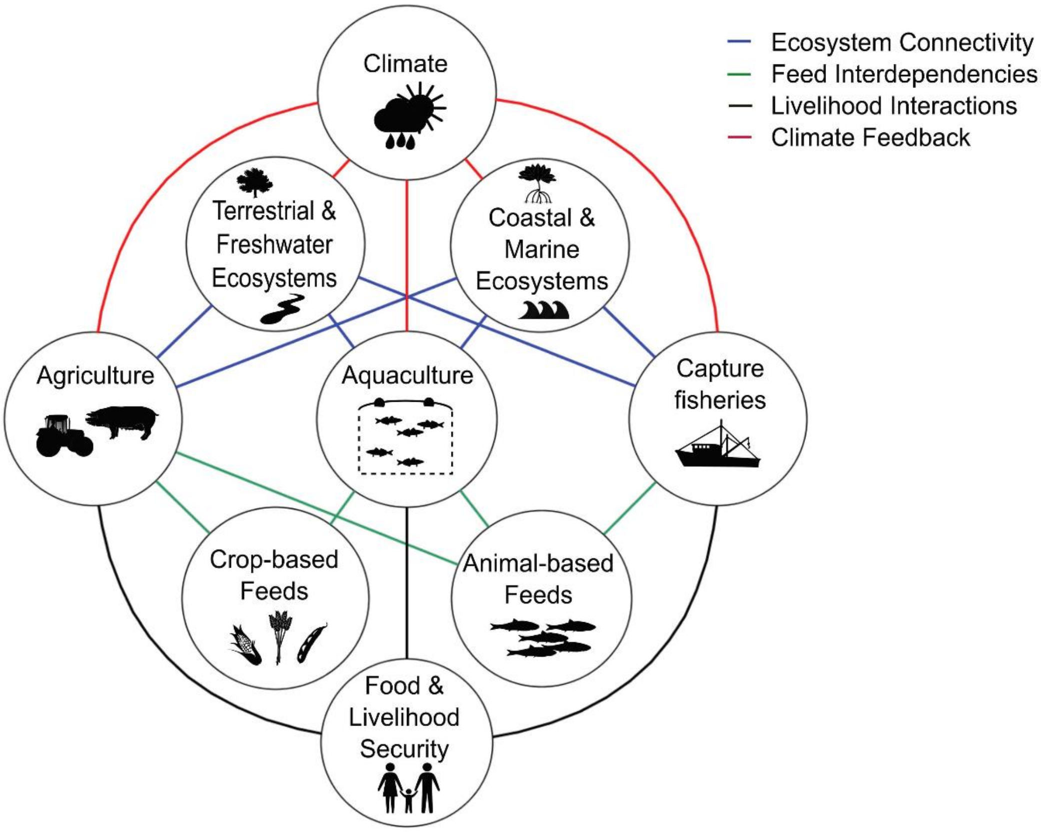

Figure 8 –The nexus of land-sea interactions among food systems. Ecosystem connectvity, feed production, human livelihoods, and climate fundamentally link terrestrial and aquatic food production systems.

Support for cross-sector research is growing, and modelling that integrates food production with social-ecological drivers of change presents a powerful approach of accounting for land-sea interactions described here. Work emerging from the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP) quantifies impacts and trade-offs among agriculture, fisheries, water, energy, agro-economics, infrastructure, forestry, ecosystems, and health sectors under climate change (www.isimip.org). The GLOBIOM model developed by the International Institute for Applied Systems Analysis (IIASA), analyses resource pressure among agricultural, bioenergy, and forestry sectors. Recent development of the ‘Madingley Model’ aims to integrate links between marine and terrestrial ecosystems in order to project human impacts at a global scale (Harfoot et al. 2014). Nonetheless, more integrative and empirical work is needed for food security research. For example, no food production model holistically incorporates both marine and terrestrial components.

Single-sector approaches to research mean that combined solutions from aquatic and terrestrial production are vastly underrepresented in major food security policies and initiatives (Fisher et al. 2017). Land-sea connectivity in the food system presents a number of challenges regarding where to set boundaries of governance and how to engage actors at local scales to promote cross-system resilience (Pittman & Armitage 2016). Matching the scale of the food security problem to the local and social contexts where solutions are enacted is a significant challenge for policy-makers. Overcoming the inherently complex and social-ecological nature of these problems, requires greater institutional support for inter-and transdisciplinary science that facilitates the exchange of diverse knowledge types among researchers, policy makers, and stakeholders (Pittman & Armitage 2016).

Specialised taskforces on food security such as the ‘UK-US Taskforce on Extreme Weather and Global Food System Resilience’ (www.foodsecurity.ac.uk) and the United Nations ‘High-level Panel of Experts on Food Security and Nutrition’ (ww.fao.org/cfs/cfs-hlpe) represent an ideal opportunity for tackling these cross-sector challenges. Comprising academic, industry and policy professionals, these panels are in a unique position to encourage discussions on single sector targets and cross-sector trade-offs. For example, participatory inter-sectoral workshops in Colombia have proved effective in illuminating cross-sector conflicts among single sector development targets, facilitating integrated development planning and multisector collaboration (Weitz et al. 2014). Bridging science and policy, these taskforces could implement similar approaches, and the High Level Panel on Food Security has already outlined that greater integration of aquatic and agricultural production is needed in future food security policies (HLPE 2014).

Directly addressing counter-productive land-sea trade-offs in the food system will require significant improvements in food production efficiency. Integrating livestock waste into crop production, greater adoption of integrated pest management strategies and shifts towards agroforestry may improve on farm biodiversity while reducing impacts on aquatic ecosystems (Godfray et al. 2010). Precision technologies can be used to optimise timings and locations of chemical/nutrient inputs to prevent surpluses building in soils (Day et al. 2008). Increasing crop productivity in low yielding areas may also reduce the need to expand cultivated land area with rising feed demands, although this will vary spatially. In some areas, returning degraded agricultural land to food production may be less environmentally costly than improving yields for example (Godfray & Garnett 2014). Diversifying food systems to integrate both aquatic and agricultural production can improve nutrient, land and freshwater use efficiency, but will also be key in increasing livelihood resilience to climate shocks in nations where food security remains a challenge (Blanchard et al. 2017). Furthermore, aquatic-terrestrial integration may provide a compromise in areas where inter-sectoral resource competition hinders food security, as with conflicts surrounding intensive shrimp farming (Paul & Roskaft 2013).

Human consumption patterns in high-income countries must also change. Diets that reduce animal-based protein intake, optimise consumption within the bounds of human health and nutrition, reduce fertiliser and feed demands, and can lower food-related emissions (Davis et al. 2016, Foley et al. 2011, Gephart et al. 2016, Tilman & Clark 2014). Domestic and commercial waste in the supply chain remains a huge source of inefficiency in the food system and may worsen with more resource-intensive diets. Global wastage of meat products alone represent crop losses sufficient to feed over 200 million people (Davis & D'Odorico 2015).

Encouraging change will be difficult. Shifting diets at the population level may depend more on price and accessibility than environmental benefits (Popkin et al. 2012). Simply redirecting feed crops and fish to human consumption also overlooks more complex socio-economic considerations, such as widespread dependence on livestock for livelihoods (Godfray et al. 2010), or distribution costs which limit poorer, rural communities' access to forage fish products (Wijkstrom 2009). Nonetheless, addressing this challenge, along with other inefficiencies in food production, will be crucial for meeting sustainability targets outlined for 2050.

2.8. Conclusions

As we strive to feed a growing population with more resource-intensive diets over coming decades, cross-sector links and interdependencies may create trade-offs for food systems on land and sea. Terrestrial food production is increasing pressure on aquatic systems through agricultural run-off and rising feed demands for livestock. In contrast, aquaculture now competes for terrestrial resources for feed to keep pace with sector growth. Improving land, pest and waste management, changing consumer diets and integrating terrestrial and aquatic production on larger scales may be central to addressing the counter-productive links driven by inefficiencies in the food system. Food security policies also need to better account for diverse livelihoods that simultaneously rely on both land and sea. Single system approaches for tackling hunger may underestimate vulnerability to global change as it reaches across multiple sectors and ecosystems. Research on how to anticipate cross-sector trade-offs in food and sustainability planning will play a pivotal role in informing policy in years to come.

Chapter 3

3. Potential for novel feeds to aid sustainable aquaculture growth

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3.1. Abstract

Fed aquaculture has historically relied on wild-caught pelagic ‘forage’ fish (e.g. herrings, sardines, anchovies) to produce fishmeal and oil as key ingredients for aquafeeds. But with the plateau of global forage fish catches, there is a race to find sustainable and nutritionally equivalent alternatives to forage fish alongside other ingredients to support industry growth, human nutrition, and environmental health. Numerous novel aquafeeds have been experimentally tested for various taxa, but whether these provide scalable solutions to meet increasing global demand without comprising human health benefits is unknown. Combining global production data, scenario modelling and a decade of experimental data on forage fish replacement using soy, algae, bacteria, yeast or insects, we show that global uptake of novel aquafeeds could substantially reduce aquaculture’s forage fish demand by 2030 while maintaining feed efficiencies and nutritional content. We further illustrate how the greatest savings can be achieved by reducing future fish oil demand, particularly from high-value species. If social, environmental, economic and regulatory concerns can be addressed, broader commercialization of novel aquafeeds could be a powerful tool for sustainable aquaculture growth.

3.2. Introduction

Aquaculture now produces greater biomass than capture fisheries and is one of the fastest-growing sources of animal production globally (FAO 2018). Rapid growth has created numerous sustainability concerns, however (Naylor et al. 2000b, Naylor et al. 2001, Pahlow et al. 2015, Fry et al. 2016), not least supplying the burgeoning feed demands of fed finfish and invertebrates (from carps and catfish to salmonids and shrimp). Feeds for fed aquatic species (‘aquafeeds’) have historically included fishmeal and oil, rendered from small pelagic ‘forage fish’ (e.g. herrings, sardines, anchovies), as sources of inexpensive and palatable protein and lipid (Turchini et al. 2019). Forage fish ingredients simplify formulated feeds because their distinctive composition matches the protein and fatty acid requirements of farmed aquatic species (Turchini et al. 2019). But forage fish use in feed has attracted considerable scrutiny in recent years, largely over the effects of extracting small fish species from marine ecosystems (Naylor et al. 2009, Naylor et al. 2000b) and the perceived inefficiencies of diverting them away from human consumption (Wijkstrom 2009). Further, with the supply of wild forage fish stagnant for decades, the price of fishmeal and oil are rising as demand from aquaculture, pig and poultry feeds continue to increase (Appendix Figure 1). To ease pressure on marine ecosystems and secure growth in the aquaculture industry, producers have and must continue to find feeds that reduce or exclude forage fish ingredients without compromising economic viability or benefits for human health. Further, these alternative feed ingredients must have low environmental impacts themselves to avoid any unwanted trade-offs of their use.

Numerous fishmeal and fish oil sparing diets have been experimentally tested, commercially synthesized, and used in feeds by aquaculture producers for various farmed aquatic species. Plant ingredients have become particularly attractive for producers as crop production continues to increase and the price gap with forage fish widens (Turchini et al. 2009). Soy, corn, cassava, wheat, canola, and many other crops have been introduced as protein and oil sources (Hasan & Halwart 2009, Turchini et al. 2009). Yet most vegetable products contain higher proportions of fibre and anti-nutritional factors (Francis et al. 2001) that can impair species growth performance, increase feed and nutrient waste (Hamilton et al. 2015), and are relatively poor sources of the omega-3 (n-3) fatty acids and micronutrients abundant in fish oil – particularly the long-chain highly-unsaturated fatty acids highly beneficial for human health (Turchini et al. 2009, Naylor et al. 2009, Kokou & Fountoulaki 2018). While these some of these issues may be overcome through supplementation, there is still an ongoing debate about the long-term sustainability of increasing pressure on already-strained crop systems (Fry et al. 2016, Froehlich, Runge, et al. 2018, Pahlow et al. 2015, Troell, Naylor, et al. 2014). Waste from the meat industry has also been used for protein and oil in many feeds. Meat, feather or bone meal can contain suitable amino-acid profiles for species growth but consumer acceptance, the saturated fat content of animal lipids, and lack of essential n-3 highly unsaturated fatty acids prevents them from being a complete solution (Naylor et al. 2009, Turchini et al. 2009). The limitations of crop or livestock waste to deliver growth or nutritional benefits have increased focus on the development of novel aquafeed ingredients to provide key protein, lipids, and nutrients to fill future deficits in forage fish supply.

Single-cell organisms (e.g., microalgae, bacteria, and yeasts) and insects are emerging ingredients of interest to reduce forage fish inclusion (e.g. Veramaris 2019), but many feeds containing little to no marine inputs often fail to yield the same growth results as those that retain forage fish ingredients (Turchini et al. 2019). With these differences among feeds, understanding the wider potential of novel feed ingredients and the uncertainty around this requires synthesising data on the growth and nutritional effects of forage fish replacement (as these are likely to drive industry decisions) across different novel feed types, farmed species, and nutritional or experimental approach. Variability in the effect of forage fish replacement among species, feed types, and experimental approach reflects the differences in regional production across the globe and once accounted for can scale to inform a global perspective of the comparative potential for novel feeds to reduce aquaculture's forage fish demand. Given global ambitions surrounding the United Nations 2030 Agenda for Sustainable Development (United Nations 2015a), and that demand for forage fish ingredients may exceed current supply by 2030 or sooner as management and demand changes (Froehlich et al. 2018b), information on the extent to which fishmeal and oil sparing feeds can reduce forage fish demand is urgently needed to support sustainable seafood production.

We fill this knowledge gap by combining published information on farmed species feed efficiencies, dietary composition, and feeding practices with national aquaculture production data, and plausible aquaculture growth scenarios, to calculate and compare projected demand forage fish demand by 2030 with the supply historically available. We systematically identify, synthesize, and model 10 years of experimental data using algae-, bacteria-, yeast- or insect-based diets for forage fish replacement to identify average responses in species feed conversion ratios (feed intake/weight gain) or nutritional content (via n-3 to n-6 fatty acid ratios). Identifying thresholds of forage fish replacement with equivalent performance to reference diets and comparing to a major feed crop – soy – we evaluate and discuss the potential for novel feeds to reduce forage fish demand into the future, including barriers to their wider adoption.

3.3. Results and Discussion

3.3.1. Reconciling aquaculture's future forage fish demand with historical supply

Reducing aquaculture's forage fish demand has been a focus of a huge body of research over the last 20 years. Shifts towards greater inclusion of crop ingredients in aquaculture feed, combined with considerable increases in feed efficiency has led to dramatic decreases in fishmeal and oil inclusion rates in the diets of fed aquatic species (Fry et al. 2016, Troell, Naylor, et al. 2014, Tacon & Metian 2015). Nonetheless, progress toward reducing fishmeal and oil in aquaculture feeds needs to continue if we are to meet increasing demands for aquatic food, as these will almost entirely be met by aquaculture (Watson et al. 2015, Freolich et al. 2018). Using discards and fish trimmings for fishmeal production or removing fishmeal from carp and tilapia species which are not naturally piscivorous are potential strategies to keep aquaculture's forage fish demand below historic supply(Froehlich et al. 2018b, Naylor et al. 2009), but even these strategies will be insufficient under current and projected species production composition (Froehlich et al. 2018b). Within the spectrum of future approaches, we ask to what extent novel aquaculture feeds can play a role in supplying feed to the growing aquaculture sector, and in turn, allow more judicious future use of forage fish.

Fed aquaculture's future demand for forage fish will depend on various economic and environmental factors influencing the aquaculture industry's growth. Building on recent work examining forage fish limits under six different aquaculture growth scenarios to 2050 (Froehlich et al. 2018b), here we focus on three key shorter-term scenarios to 2030 to explore this uncertainty. We use United Nations aquaculture growth projections (FAO 2018) as our business-as-usual scenario (2030 BAU), and two alternate futures based on World Bank's IMPACT model projections (World Bank 2013). The first is a scenario of more rapid growth that may be seen with greater shifts towards pescatarian diets (World Bank 2013, Tilman & Clark 2014) (2030 Rap.Gr); the second is a scenario reflective of accelerating consumer preference for high-value seafood in China already being observed with increasing affluence and demographic change (World Bank 2013) (2030 Cons.Shft) (Table 1). For each scenario, both the change in total production quantity and the composition of production across different countries and aquatic taxa (with differing diets and efficiencies) contributes to varying levels of forage fish demand (Appendix Figure 2).

Table 1 – *Aquaculture growth scenarios used for future forage fish demand calculations*

Production Scenario	***Description***	***Global Δ production relative to 2015 (%)***
2030 BAU	*Based on projected production increases by 2030 from the FAO* (FAO 2018)*. MEDCs expected to increase production by 28%, 46% in least developed countries, and 36% everywhere else.*	+37
2030 Rap.Gr	*Reflects the 'Faster aquaculture growth' scenario from World Bank* (World Bank 2013)*. Production predicted to grow 50% faster than BAU in all countries.*	+56
2030 Con.Shft	*Growth rates mirror 'Accelerated shifts in consumer preference in China' scenario from World Bank* (World Bank 2013)*. Production of salmonids, shrimps, crustaceans and tunas triple BAU tonnage, all other groups held at BAU.*	+98

Each of these scenarios represents the production response to plausible short-term projections of fish demand. Our 2030 BAU aquaculture growth scenario reflects the projected changes in population and affluence which are expected to (at least in part) drive fish (including invertebrates) consumption from 20.3 to 21.5 kg per capita per year by 2030, which results in approximately 30 million tonnes more fish required in live weight (FAO 2018). Most of this demand is expected to be filled by aquaculture, although annual growth in production is expected to slow largely due to reduced growth in Chinese aquaculture (FAO 2018). Changes in per capita demand may not be linear, however, as disproportionate increases in fish demand or the composition of fish demand relative to previous trends may occur as diets shift due to social norms, concerns over environmental impacts, or changing tastes and affluence (Tilman & Clark 2014, Springmann et al. 2016, World Bank 2013, Godfray et al. 2018, Willett et al. 2019). The other two scenarios reflect just two of the multiple possible permutations. The 2030 Rap.Gr scenario reflects a faster aquaculture growth that may be expected if diets change to contain proportionally less meat but more seafood such as the Mediterranean or pescatarian diets described in Tilman & Clark (2014). Although the World Bank scenario we use reflects a more conservative version of these at only 56% increase. The increases to salmon, shrimp, and other crustacean production realised with the 2030 Cons.Shift scenario reflects the demographically driven demand and production responses for high-value species already starting to be witnessed in China (World Bank 2013, Xinhua 2019). Despite calls for farming lower trophic level species rather than more resource-intensive taxa such as salmon (Klinger & Naylor 2012), we assume here that as an industry comprised largely of private entities, aquaculture's response to growing demand will largely be driven through economics and consumer demand.

The global supply of forage fish has remained stagnant since 1980, fluctuating around an average of 29 million tonnes, and approximately 70% of these landings have been used for animal feeds (Figure 9a). Of the fraction used for feed, an increasing proportion has been used by aquaculture (Figure 9a) which we estimate to be 16.9 million tonnes in 2015 (SD $\pm$ 364215 tonnes based on 500 simulations) in close agreement with recent estimates (Froehlich et al. 2018b). Under current feeding practices, we calculate that this demand would increase to over 24 million tonnes by 2030 under a BAU scenario, to over 27 million tonnes under more rapid industry growth, and approximately 38 million tonnes with accelerated demand for high-value species from Chinese consumers, far exceeding historical supply of forage fish (Figure 9b). However, there is great uncertainty around future supply. Forage fish populations are highly variable, closely coupled to environmental conditions and can be sensitive to fishing pressure (Essington et al. 2015). Moves towards ecosystem-based fisheries management (EBFM) of forage fish have suggested 20% catch reductions (equal to 23 million tonnes at the global level) could help improve ecosystem effects of extraction (Smith et al. 2011) and promote long-term prospects of their use in feed or for human consumption. If implemented, these management decisions would reduce forage fish availability even further (Figure 9a). Our estimates show that forage fish supply under the EBFM scenario would be lower than or equivalent to the projected demand of aquaculture alone in all 2030 growth scenarios using current diets (Figure 9b; Froehlich et al. 2018b). Uncertainties concerning both future demand and plausible reductions in supply mean that understanding where the greatest forage fish savings can be made in aquaculture feeds is central to supporting sustainable industry growth (Froehlich et al. 2018b).

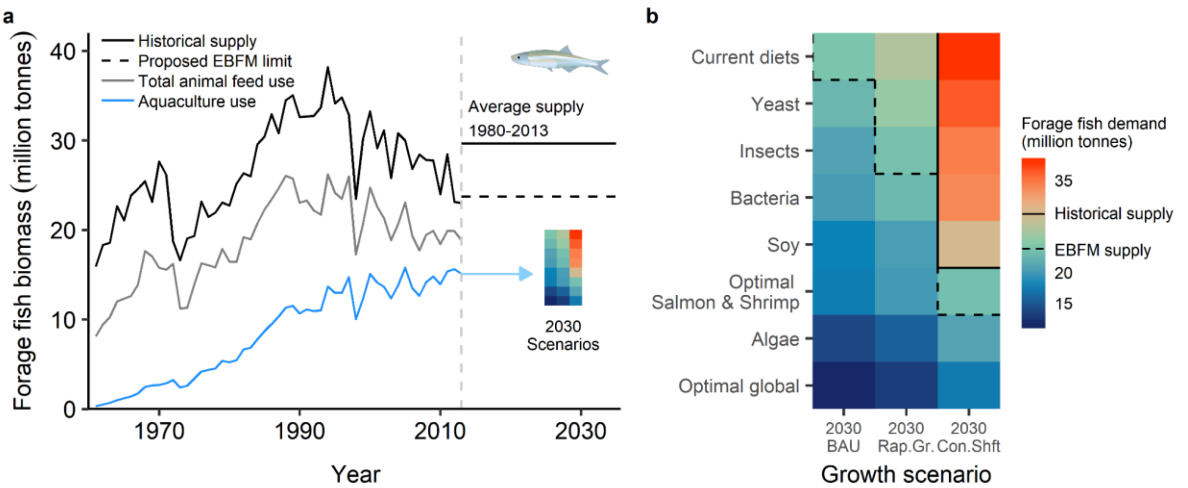

Figure 9 –Historical supply, feed use, and projected demand for forage fish across 2030 growth scenarios and novel aquafeed types. a) Historical supply of forage fish taken as landings of the top 20 forage fish species by biomass from (FAO 2019b) which make up over 90% of reported global forage fish landings (Froehlich, Jacobsen, et al. 2018). Aquaculture use through time estimated by interpolation and extrapolation of the proportion of forage fish feeds used by aquaculture in 1960, 1980, and 2010(Shepherd & Jackson 2013) and applied to FAOSTAT feed use data (FAO 2019a). b) Simulated forage fish demand from aquaculture in 2030 across different diet (current and combinations of novel feed use) and aquaculture growth scenarios. Tiles to the right of the solid and dashed lines

indicate scenarios where forage fish demand exceeds historical or EBFM supply limits respectively.

3.3.2. Global potential of novel aquafeeds

Among novel aquafeeds, we find the greatest potential for reducing forage fish demand in microalgae-based feeds. Under the 2030 BAU scenario, global uptake of microalgae-based feeds decreased aquaculture's forage fish demand below that of 2013, and in both the rapid growth (2030 Rap.Gr) and consumer shift scenario (2030 Cons.Shft.) forage fish demand stays well below the more conservative EBFM limit (Figure 9b). In contrast, while bacteria- and soy-based feeds keep demand below EBFM limits for the BAU and Rap.Gr. scenarios, bacterial, insect, yeast, and soy feed all fail to do so under a scenario of Chinese consumer shifts, with demand exceeding historical supply (Figure 9b). In both BAU and Rap.Gr. scenarios, worldwide uptake of soy-based aquafeeds deliver the second greatest savings for individual feed types, only increasing demand by 5 million tonnes under the BAU scenario relative to 2013.

When novel feeds are applied optimally (i.e. using the feed type that yields the greatest forage fish savings for each taxon), forage fish savings are even more dramatic. Under 2030 BAU and Rap.Gr. scenarios demand is reduced even below that of 2013 by 4 and 2 million respectively and global demand is limited to 17 million tonnes under the 2030 Cons.Shft scenario (Figure 9b). Although these results provide insight into the wider potential of aquafeeds, it is obviously unrealistic to expect that individual novel feed types or optimal utilization of novel feeds be applied to fish diets at a global level. Market access to novel feeds, the value of the target species, the scale of production, the culture system, financial resources at the farm level, and feed cost will ultimately control utilization by producers (FAO 2018, Sprague et al. 2017, Tacon & Metian 2015). Nonetheless, applying optimal use of novel aquafeeds to only salmonid and shrimp diets (under an assumption that producers of high-value products may be able to access new feeds sooner) still reduces forage fish demand in all 2030 scenarios below historical and stricter EBFM supply limits (Figure 9b). The drivers behind these patterns can be explained by examining the varying efficacies of different novel aquafeeds for sparing for both fishmeal and oil in the diets of different aquatic taxa.

3.3.3. Novel feed ingredients in fishmeal and oil sparing

A swathe of experimental research has focused on the capacity for novel feeds to replace fishmeal or oil in the diets of farmed fish. Interest in algal species has grown because they are rich sources of both protein and lipids (Shah et al. 2018). Importantly, some microalgae species naturally synthesise key omega-3 polyunsaturated fatty acids (e.g. eicosapentaenoic and docosahexaenoic acid; EPA and DHA respectively) crucial for the energetic and growth needs of many farmed species (Shah et al. 2018). They also correspond to the nutritional supply of fishmeal and oil which represents an added market value. Bacterial-based feeds have attracted attention because of their high protein contents and capacity to be grown on low-cost substrates with minimal land or water footprints (Mahan et al. 2018, Rosas et al. 2018). Yeasts have shown promise as protein sources for fishmeal sparing too – they possess favourable amino acid compositions relative to fishmeal and can be produced from lignocellulosic biomass such as agricultural or forestry waste (Øverland & Skrede 2017). The use of insects as protein sources in aquafeeds is also being explored. Silkworm, mealworm, or blackfly and grasshopper larvae can convert organic side-stream products (manure, cellulosic, or human food waste) into protein-rich feed-stuffs (van Huis 2013, Henry et al. 2015). However, the quality of substrates influences the value of insects as feed. Low-quality substrates often yield low-quality lipids, poor feed conversion ratios, or failure to reach harvestable size (Henry et al. 2015, van Huis 2013, Sealey et al. 2011, Lundy & Parrella 2015), which brings into question whether the high-grade feed resources required would be better fed directly to fish. While the environmental, economic, and social trade-offs associated with novel feed ingredients will be central to their scalability and uptake by farmers, here we focus on their global potential within the context of their influence on farmed species feed efficiency and nutritional content.

From a systematic search of the literature, we identified 263 scientific articles relevant to our search criteria covering 12 animal groups across algal, bacterial, yeast, soy, and insect ingredients, replacing either fishmeal, fish oil or both (*see* Methods). We limited our analysis to aggregates of carps, catfishes, tilapia, other freshwater fishes (e.g. snakeheads, Striped Bass, Nile Perch) shrimps, salmonids and marine fishes (e.g. groupers, Atlantic cod, Red Drum), however, as an insufficient number of studies for other groups prevented model fitting, and the taxa we focus on contribute over 90% of global forage fish demand (Appendix Figure 2). A large proportion (42%) of all studies addressed marine species largely due to the richness of species farmed and over half (53%) of the studies used soy as the target ingredient. Of the novel feeds, algae (17.9%) and insects (16.7%) represented the greatest proportion of the studies highlighting the uneven effort across experimental fishmeal replacement work that focuses on feed efficiency.

In general, fishmeal replacement in feed tends to increase species' feed conversion ratios (i.e. more feed is required for a given mass gain, making the feed less efficient) (Figure 10). Overall, insect-based diets had the least (median effective replacement = 100%), and soy the most (median = 50%), detrimental effect on feed conversion ratios when replacing fishmeal on average across all animal groups (Figure 10, Appendix Table 2). But there is considerable variability around these trends within feed and animal groups and among studies (Figure 10). For instance, on average no clear change to carp feed conversion ratios occurred with 100% fishmeal replacement under algal, bacterial or insect feeds. Yet, soy-based diets led to clear increases in feed conversion ratios after just 35% fishmeal replacement (Figure 10). We, therefore, reiterate how influential feeding or supplementation regimes, complimentary ingredients, species, or production systems are for the utility of novel feeds.

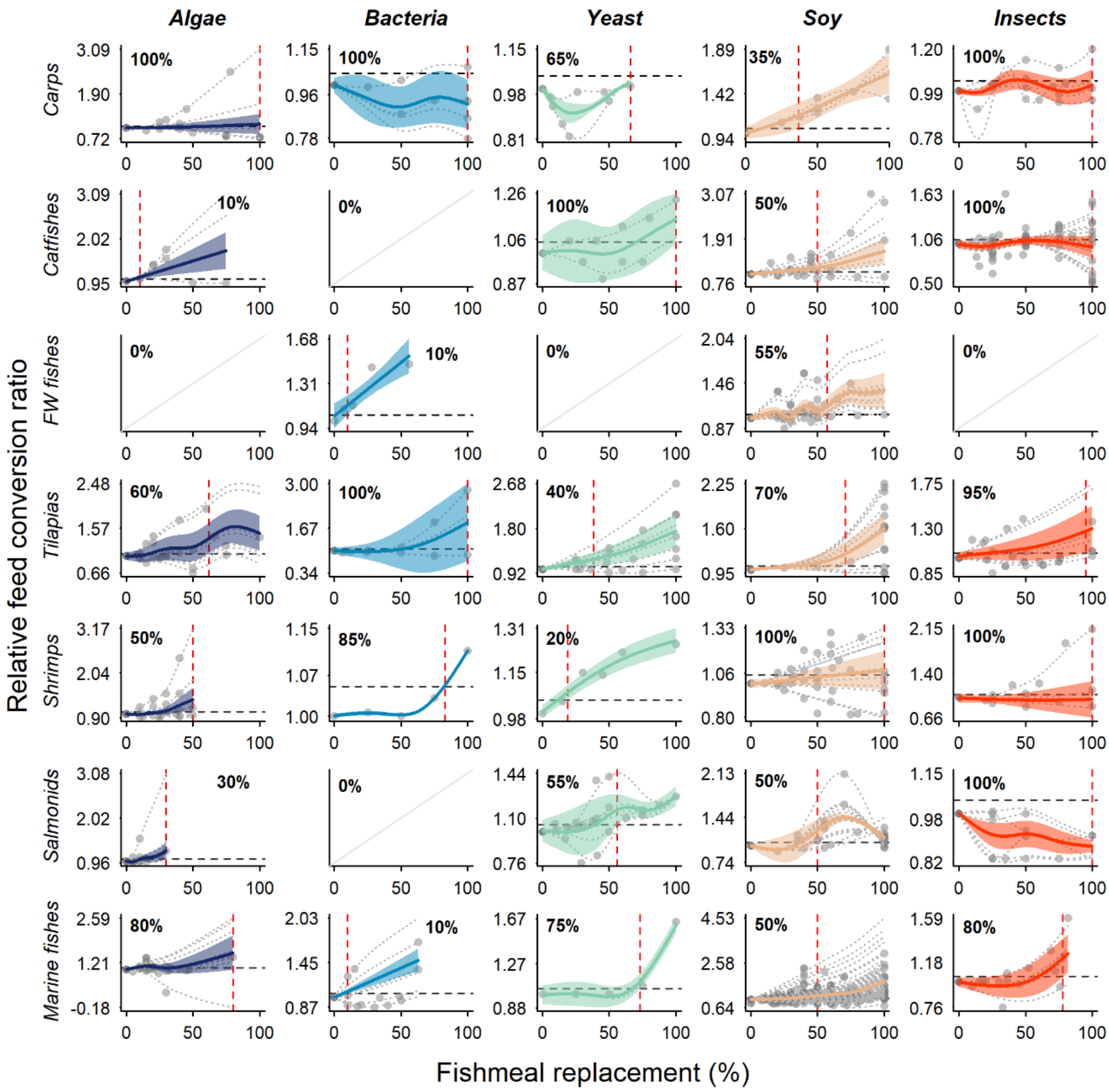

Figure 10 – Relative change to feed conversion ratios with fishmeal replacement for different animal groups across novel feed types. Solid coloured lines and shading represent fitted mixed-effects model mean response and 95% confidence intervals respectively. Vertical dashed lines in red indicate plausible fishmeal replacement level before

feed conversion rates increase beyond 5% (horizontal dashed line) of reference diets (see Appendix Table 4). Percentages in bold on each plot represent thresholds to the nearest 5%. Plots with diagonal lines indicate no/insufficient data identified by systematic search.

Taxa are affected unevenly by minimising fishmeal use in feeds. Across all the novel feed types, a median of 100% of fishmeal in carp diets could be replaced without statistically clear increases in feed conversion ratios (Figure 10). A median of over 70% of fishmeal could also be replaced without clear change to feed efficiencies across feed types for catfishes, tilapias, shrimps and marine fishes (Appendix Table 2). More carnivorous freshwater fishes and salmonids responded poorly to fishmeal replacement across feed types on average (median = 52.5% replacement threshold), largely due to feed conversion ratios increasing quickly under bacterial-based feeds (and the extent of fishmeal replacement data for algal diets in the case of salmonids) (Figure 10). Thus, highlighting the comparative physiological ease for forage fish replacement in non-obligate carnivores and a continual challenge for species like salmon.

Formulating novel feeds requires identifying and combining complementary raw materials that meet the requirements of the farmed animal(Turchini et al. 2019). Consequently, with fishmeal replacement there is often a reshuffle in ingredient contributions, including fish oil. Given many freshwater species (e.g. carps, catfishes, and tilapias) do not usually need fish oil within their diets, no clear changes in fish oil inclusion occurred with the threshold of fishmeal replacement indicated above in these species (Appendix Figure 3). But for freshwater fishes, salmonids and marine fishes fed soy-based diets to replace fishmeal, there was an increase of 1-1.5% inclusion of fish oil at the fishmeal replacement threshold (Figure 10; Appendix Figure 3). More commonly, fishmeal replacement in marine fishes led to decreases in fish oil inclusion at the threshold indicated using algae, bacteria and insect-based feeds (Appendix Figure 3). Fish oil replacement, however, did not clearly affect feed conversion ratios on average in the studies identified (Appendix Figure 4). We therefore investigate the potential of fish oil replacement by novel feeds by identifying where clear changes to nutritional content occur.

Lipids in feeds are important sources of fatty acids for regular growth, health, and maintenance in farmed aquatic species, and all fish require both n-3 and n-6 polyunsaturated fatty acids (Turchini et al. 2009). Fish oil is a rich source of many essential fatty acids, particularly n-3 highly unsaturated fatty acids (Turchini et al. 2009) and its substitution within feeds can influence the lipid composition in animal tissues, and ultimately its nutritional value for human consumption. Many different fatty acid profiles in animal tissues are of interest when formulating feeds to replace or reduce forage fish inclusion such as total n-3 or total polyunsaturated fatty acids, or the ratio of EPA to DHA (Alhazzaa et al. 2018). We assess nutritional content through relative proportions of n-3 and n-6 fatty acids – a unitless metric of the degree of change within animal tissues common to most studies and a useful proxy of the animal's nutritional content (*see* Methods).

We identified fish oil replacement experiments largely focused on three main animal groups – shrimps, salmonids, and marine fishes – the main consumers of fish oil globally (Tacon & Metian 2008). Of the five replacement ingredients, algae and soy both produce oils that are widely experimented with for replacing fish oil (one study for fish oil replacement by yeast was omitted due to insufficient data for modelling). Compared to soy, algal diets showed greater promise in fish oil minimisation on average, with 100% of fish oil able to be replaced in shrimps and marine fishes without clear changes to the ratio of n-3 and n-6 fatty acids in animal tissues (Figure 11). Using soy oil allowed 100% fish oil replacement in marine fishes without clear change to n-3:n-6 fatty acid ratios, but only 30% in shrimps (Figure 11). Once again, salmonids did not respond as well as other groups to fish oil sparing in general. Significant reductions in n-3:n-6 ratios occurred on average after 55% fish oil replacement with algal feeds, and only 10% with soya oil (Figure 11). Differences in feed efficiency across animal groups such as these will mean different producers and sectors will favour one product over another rather than uniform uptake of single feed types.

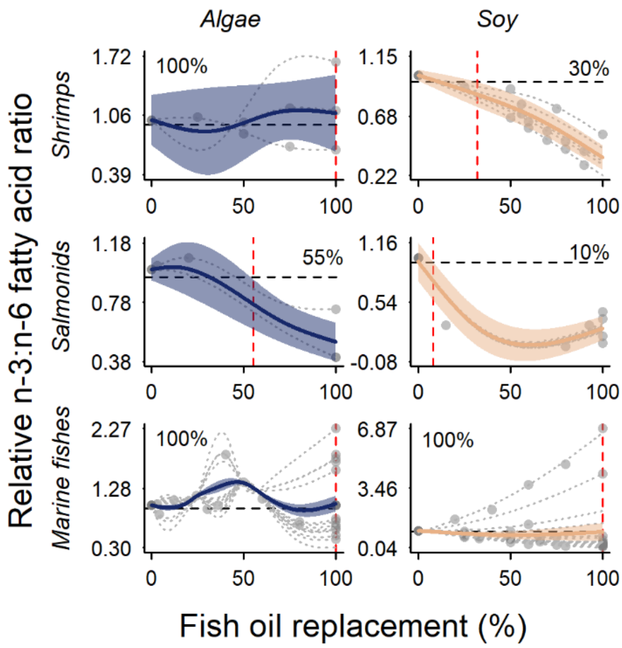

Figure 11 – Relative change to n-3:n-6 fatty acid ratio in species tissues with fish oil replacement. Solid coloured lines and shading represent fitted mixed-effects model mean response and 95% confidence intervals respectively. Vertical dashed lines indicate threshold where n-3:n-6 fatty acid ratios decrease beyond 5% of reference diets (horizontal dashed line). Percentages on each plot represent thresholds to the nearest 5%. Only whole body and fillet samples were used for fatty acid data. All values on plots are summarised in Appendix Table 3.

3.3.4. Optimising forage fish savings

Greater comparative efficiency of algae and soy in reducing global forage demand (Figure 9b) come largely from their capacity to reduce fish oil, which converts far less efficiently into forage fish equivalents (Tacon & Metian 2008). This is illustrated in our analysis by some of the greatest global forage fish demands across all scenarios persisting with use of insect-based feeds (Figure 9b), despite their superior capacity to replace fishmeal (Figure 10; Appendix Table 2). The greatest savings in forage fish biomass under all 2030 scenarios can be gained through novel feeds that most effectively reduce fish oil inclusion (here, algae and soy) in taxa most dependent - shrimps, salmonids, and marine fishes (Figure 12a-e). Savings are most exaggerated under a scenario of accelerated consumer shifts to high-value species and particularly when large proportions of fish oil can be reduced in salmonid feeds (as in algae; Figure 12a). Fish oil sparing will also be an important step in growth of blue economies worldwide too. Under a scenario of more rapid growth and as operations move offshore(Lester et al. 2018), greater production of marine species will likely drive increased demand for fish oil which remains a key component in marine fish diets (Tacon & Metian 2008, Froehlich, Runge, et al. 2018). Addressing this demand through either partial or complete fish oil elimination using novel feeds will be an important saving to reduce aquaculture's demand for forage fish. Continued targeting of fish oil reductions in feeds for salmonids, shrimps and marine fishes at a global level, therefore, provides a key intervention point for dramatically reducing future forage fish demand (Figure 12).

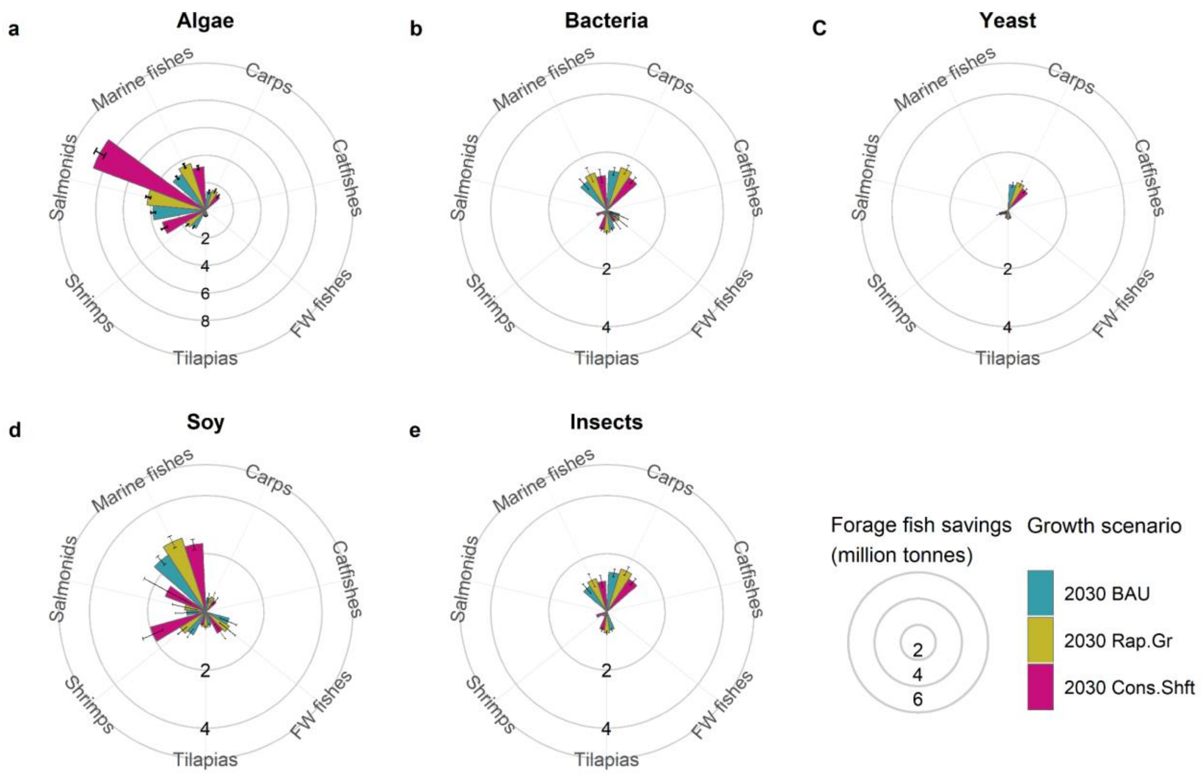

Figure 12 – Simulated global forage fish savings across animal groups with incorporation of novel feed ingredients under different aquaculture growth scenarios to 2030. Bars represent mean savings across 500 simulations for each scenario and error bars represent the standard deviation. Savings calculated as demand with current diets minus demand given plausible fishmeal and oil replacement for each novel ingredient. Note algae is on a different scale to other feed types due to very large savings from salmonids under the 2030 Cons.Shft. scenario.

Our analysis illustrates the huge potential for novel aquafeeds to reduce aquaculture's demand for forage fish and the marine ecosystems that support them but highlights several hurdles that producers will face regarding their utility. For example, algal oils (e.g. from *Schizochytrium spp.*) will be key ingredients for reducing aquaculture's dependence on fish oil but their relatively small production volume still provides a very small market contribution compared with traditional commodities (Vigani et al. 2015). Further, it is also unclear how the relative impacts of these novel feeds will scale as they grow to a commercial volume. The high expense of extracting algae oil from biomass and complications protecting long-chain polyunsaturated fatty acids against oxidation once extracted also compound costs (Sprague et al. 2017). Social acceptance of new feed ingredients will also play a role in market success, particularly if genetic modification occurs to improve desirable fatty acid profiles, as has been tested with camelina and canola oils (Sprague et al. 2017) and canola is now under commercial production in the United States (Napier et al. 2019). Furthermore, regulatory restrictions on the safety and nutrition of novel products that lead to extensive assessments can slow expedient market release and the pace of commercialization (Vigani et al. 2015). Nonetheless, progress toward commercial-scale production of novel feeds is gaining pace with black soldier fly larvae and mealworms gaining approval for inclusion in EU aquafeeds in 2017, and commercial-scale role out of salmon feeds containing microalgal meal and oils in 2019 (Skretting 2017). Importantly, consumer awareness of feed sustainability issues is growing along with acceptance to pay premiums for responsibly produced food (Llagostera et al. 2019, Veramaris 2019), and these trends will likely bolster future uptake.

Crucially, we show that reducing aquaculture's forage fish demand below even conservative future supply levels can be achieved with modest reductions in marine ingredients in aquafeeds. With salmonids the largest consumers of fish oil globally (Tacon & Metian 2008), dramatic forage savings can still be achieved with just over half of fish oil inclusion without any clear change to the nutritional content of the fish (based on the n-3:n-6 ratio). If, as we assume, future demand for fish oil is likely to determine absolute demand for marine resources (Naylor et al. 2009), this will be an important step toward sustainability for the aquaculture sector as it strives to meet growing demands for aquatic food. Use of whole "trash fish" for feed from low-value fisheries and discards will likely continue to supply animal protein to farmed species in some countries (e.g. China) instead of proper and adequate compounds feeds (Cao et al. 2015). While we do not explicitly model the use of these resources, our range of dietary fishmeal inclusions and feed conversion ratios are extremely conservative across taxa compared to China-specific values (Chiu et al. 2013), and deliberately underestimate demand coming from these massive systems to account for diverse sources of fishmeal and oil. However, it is likely that the fishmeal and oil contributions of aquatic by-products will grow into the future as they are rich in essential fatty acids and avoid debates over food versus feed (Turchini et al. 2009, Turchini et al. 2019).

Optimism surrounding the potential of novel aquafeeds to reduce pressure on marine ecosystems must also be tempered by uncertainties surrounding the topic. Experimental work on the capacity for novel feeds to replace forage fish has been highly skewed toward juvenile life-stages (92% of studies within our analysis were conducted on juveniles). Understanding the sustainability of feeds also needs greater scrutiny, beyond their capacity to replace marine ingredients to mitigate any unwanted trade-offs from their use such as greenhouse gas emissions or the change in environmental footprint on non-target ingredients (Couture et al. 2019, Pelletier et al. 2018) – particularly as impacts from experimental production can be very different to commercial scale. While algal feeds can perform well in terms of cumulative environmental energy extraction compared with reference fish feeds, performance depends heavily on feed composition and fossil fuel use may still be higher (Taelman et al. 2013). Similarly, insects show promise as analogues to fishmeal in aquafeeds (Figure 10) but feed conversion ratios and overall energy use can be as high as conventional livestock (Oonincx et al. 2010, Oonincx & de Boer 2012, Lundy & Parrella 2015). This reinforces the need for research to address the greatest complementarities in feed between novel and traditional ingredients, which optimise not only growth rates of farmed species but the most judicious use of forage fish and other natural resources.

It is also important to acknowledge that while our study highlights the potential for novel feeds to reduce forage fish demand from fed aquaculture, this does not necessarily translate to reduced fishing pressure on forage fish stocks or the marine ecosystems that support them. For example, if the salmon industry were to dramatically decrease their demand for forage fish in response to public perceptions, this may have a positive price effect, and lead to increased use of forage fish in the feed of other fed aquatic species such as shrimp or tilapia. Both of these taxa are largely produced in Asian countries where economic production efficiency rather than social licence are the driving factors for feed composition (Cao et al. 2015). Given the lucrative nature of forage fisheries at a global scale it is likely that this forage fish resources will be used to full capacity where available (Froehlich, Jacobsen, et al. 2018). While these feedbacks are not explicitly accounted for in our analysis, we recognise their importance in terms of realised pressure on forage fish populations.

Reducing demand and the prevention of collapses of forage fisheries will depend on stricter management (Essington et al. 2015). Management strategy evaluation has shown that understanding life histories of targeted forage fish species can help manage the trade-offs among total catch and catch stability, and help predict the natural fluctuations in productivity that are amplified by default harvest strategies (Siple et al. 2019). More precautionary management can also limit the potential broader ecosystem effects from forage fisheries that can negatively influence perceptions of aquaculture feed sustainability (Smith et al. 2011).

Achieving sustainable growth of fed aquaculture will require reduced global dependence on forage fish ingredients. Keeping aquaculture's demand for forage fish below historical supply limits is already possible using novel feed ingredients currently available, although with varying potential across species and economies. Naturally non-piscivorous fish such as carps, and tilapias respond well to complete fishmeal elimination from feeds but economic access to suitable novel ingredients may limit widespread uptake in the short-term. In contrast, high-value species such as salmonids appear more sensitive, becoming less efficient in feed to weight gain and/or less nutritionally beneficial with only partial forage fish replacement. Nonetheless, modest reductions in fish oil demand from salmonids, shrimps and marine fishes globally yield the greatest reductions in global forage fish demand, thus current innovations targeting reductions in fish oil show great promise for sustainable growth of fed aquaculture. Future work on novel feed development should aim to prioritise low-cost and complementary ingredients that may be more widely accessible to low economic value production systems which otherwise depend on aquatic resources with poor economic, social, and environmental efficiency. Further investigations on novel aquafeeds across all dimensions of sustainability are needed as shifting human dietary preferences and demographic change may drive rapid increases in demand for seafood in the next decade. It is important to recognise that these developments should also occur alongside growth in production of species that are less dependent on feed – a challenge that will need to account for consumer tastes and demand, health benefits and economics.

3.4. Methods

We synthesized a broad body of published datasets and scientific literature on aquaculture growth, the potential of novel feeds to replace forage fish ingredients, and current and future forage fish demand. By first combining national aquaculture production data with published information on farmed species growth efficiencies, dietary composition, and industry growth scenarios, we calculated and compared historical forage fish supply with projected demand by 2030 under different growth scenarios. To understand how alternative novel feeds can help ameliorate disparities between historical forage fish supply and projected demand, we then assembled a broad body of published experimental data on fishmeal and oil replacement by novel feed ingredients to model their influence on species growth and nutritional content. While assuming reasonable tolerance thresholds for producers, we applied these results to previous forage fish demand calculations to assess if novel feeds alone will be sufficient to keep the demands from fed aquaculture below the historical supply of forage fish. We performed all data analyses in this study using R statistical software (R Core Development Team 2017).

3.4.1. Aquaculture growth scenarios

For production biomass values for fed aquaculture species until 2015, we used data from the FAO FishStatJ database (1950-2015 Global production dataset: www.fao.org/fishery/topic/166235/en). We then used published growth scenarios to calculate plausible production potential by 2030 which enabled us to simulate future forage fish demand. The first scenario from the FAO (2030 BAU) simulates 37% increase in aquaculture growth in developing countries, 28% in developed nations and 46% in Least Developed Countries (FAO 2018). We drew the other two scenarios from the World Bank's IMPACT model projections (World Bank 2013). Our second scenario (2030 Rap.Gr) addresses the possibility of faster aquaculture growth with technological progress that enables the supply of a given unit of biomass at a lower cost (World Bank 2013). This may be particularly relevant if demand for fish increases under shifts towards more pescatarian human diets in the future (Tilman & Clark 2014, Froehlich et al. 2018b). Under this scenario, we increased growth rates from BAU by 50% (World Bank 2013). The third scenario for production in 2030 (2030 Cons. Shft) reflects a case where increasingly affluent Chinese consumers increase demand three-fold (mirrored by production change) for high-value products such as salmon, shrimp and other crustaceans (Appendix Figure 2).

3.4.2. Calculating forage fish demand

To calculate current and future forage fish demand, we employed the generalized modelling approach of Froehlich et al (2018b). Across the three different production scenarios outlined above (2030 FAO, 2030 Rap.Gr, 2030 Cons.Shft) we calculated forage fish demand for fish group *i* in country *j* as:

$$FF_{ij} = Prod_{ij} \cdot Prop_i \cdot FCR_i \cdot FMFO_i \cdot Cv \qquad \text{Eq. 1}$$

where demand (*FF*) is the product of production biomass (*Prod,* 2015 or 2030), the proportion of biomass that are fed (*Prop*), the feed conversion ratio (*FCR*; feed input divided by biomass output), and proportional dietary contribution of fishmeal and oil (*FMFO*) converted into biomass equivalents of forage fish (*Cv*) (Tacon & Metian 2008).

We took ranges of values for proportions of biomass that are fed and dietary contributions from fishmeal and oil from Tacon and Metian(2008), and feed conversion ratios from Froehlich et al (2018b). For each animal group in each country, we sampled randomly from the uniform range of values presented in Appendix Table 4 to account for regional differences in production efficiencies and feed practices that influence forage fish demand. We then run each forage demand simulation 500 times to obtain mean demand while quantifying uncertainty from between- and within-country differences.

3.4.3. Forage fish replacement data

To identify relevant data on the growth and nutritional effects of fishmeal and oil replacement by novel feeds, we conducted a systematic search of experimental aquaculture literature. We focused on soy as the major crop-based substitute for forage fish along with novel ingredients not yet a substantial global source of human food – algae, bacteria, yeast, and insects. In Google Scholar and Scopus databases, we applied the predefined search terms outlined in Appendix Table 5 for each feed ingredient separately. Different search terms within each ingredient were defined through a preliminary search of Google Scholar using (for example) “algae” or “bacteria” with the rest of the search string to find common model organisms to include. We defined animal group terms by the broad groups and key species outlined in Tacon and Metian (2015) and Pahlow et al. (2015) and subsequently adjusted through the same process as outlined above for feed ingredients. In Scopus, all searches looked for the search terms in document titles, abstracts and keyword fields, and we reviewed all results returned for inclusion in our study. In Google Scholar, we reviewed all items returned until five consecutive pages yielded no further relevant studies as is consistent with systematic search methods (Pickering & Byrne 2014).

For an experimental study to be included in our analysis, it needed to:

- Be published between 2008 – 2018 to isolate recent trends in the growth and nutritional effects of forage fish replacement.
- Replace fishmeal and/or oil ingredients using soy, algae, bacteria, yeast or insects (solely or in combination with other ingredients).
- Explicitly illustrate forage fish sparing rather than supplementation with novel feed ingredients.
- Numerically (not just graphically) describe the influence of fishmeal or oil replacement on animal growth through the feed conversion ratio (or the feed efficiency ratio where we took the inverse).
- Numerically (not just graphically) describe the influence of fish oil replacement on the nutritional value of animal tissue through the n-3:n-6 fatty acid ratio (or the n6:n3 fatty acid ratio where we took the inverse).
- Detail the complete dietary composition of reference (0% forage fish replacement) and experimental diets so we may quantify trade-offs between fishmeal replacement and dietary fish oil (and vice versa) and account for them when calculating forage fish demand.

3.4.4. Metrics for growth efficiencies and nutritional content

There are a number of indices that experimental studies and producers use to assess growth rates and the nutritional value of farmed aquatic animals at the start of, during and after feeding trials. Growth parameters can include a combination of total weight gain (percentage change between final and initial weight), specific growth rate (difference in natural logarithm of final and initial weight normalised by duration of feed trial), feed efficiency ratio (weight gain divided by feed input), feed conversion ratio (feed input divided by weight gain), or protein efficiency ratio (weight gain divided by protein input). Here we adopted the feed conversion ratio as our growth metric of interest firstly because the results directly reflect the forage fish demand calculations. But secondly, feeds are one of the greatest overheads for aquaculture producers (e.g. 50% of total production costs for salmon) (Føre et al. 2018) and significant increases to feed conversion ratios may equate to lower profits per unit of biomass produced.

As a metric of nutritional value in farmed species tissues, we adopt the ratio of omega-3 to omega-6 fatty acids (n-3:n-6) within animal tissues following fish oil replacement trials. We note that decisions on nutritional substitutability of a given feed ingredient normally use several metrics of fatty acid content including total n-3 polyunsaturated fatty acid content, total eicosapentaenoic acid (EPA) (Fontaneto et al. 2011, Turchini et al. 2009), total docosahexaenoic acid (DHA) content, or a ratio of the two among others (Alhazzaa et al. 2018). Nonetheless, the relative proportions of omega-3 and omega-6 fatty acids provide us with a useful, unitless metric of the degree of change within animal tissues. This change is also significant for the nutritional value of a farmed species for human consumption. Low n-3:n-6 fatty acid ratios present in western diets are implicated in the origination of cardiovascular disease, cancer and auto-immune diseases (Simopoulos 2002). While omega-3 rich seafood are heralded for their suppressive effects on such diseases (Willett et al. 2019, Béné et al. 2015), a reduction of n-3:n-6 fatty acid ratio in the tissues of farmed species moves their nutritional value away from these benefits. Although, the ratio we use may mask real decreases or increases to the absolute done content of omega-3 fatty acids in species' tissues, replacement of forage fish is often done using ingredients that are considerably richer in omega-6 ratios such as plants or terrestrial insects (Fontaneto et al. 2011, Turchini et al. 2009). If this ratio lowers only due to increases in omega-6 while omega-3 levels remain static, we argue that shifts towards a lower ratio within a given portion may ultimately lead to decreases in the health benefits we detail above. However, we do also note that other health benefits exist for certain omega-6 fatty acids such linoleic acid and micronutrients that we do not take into account in the content of fish tissues (Hicks et al. 2019).

From each study we extracted the mean effect of forage fish replacement on either the feed conversion or fatty acid ratios to represent a single point within our data. To judge plausible replacement levels of fishmeal and oil, we assumed producers will only be willing to replace forage fish ingredients in feeds if a reasonably similar feed conversion ratio or fatty acid profile is achieved. We arbitrarily hold this similarity to within 5% of reference diets, given there will be a price or even belief system component to why a manufacturer or producer may want to use a novel feed over fishmeal and oil. We standardise the detection of any change beyond this threshold as the point in which 95% confidence intervals of fitted statistical models (detailed below) increase or decrease more than 5%. past reference diet values for feed conversion ratios or n3: n6 ratios respectively.

3.4.5. Modelling growth and nutritional effects of forage fish replacement

Given the range of fed animal species, ingredient species or forms, amino acid or enzyme supplementations, attractants, pellet sizes, or production environments used, it is not surprising that even studies replacing forage fish with the same ingredients within animal groups yield different results for growth or fatty acid contents. To account for these differences, we combined experimental data for each feed type and animal group and model at what level of forage fish replacement feed conversion or n-3:n-6 fatty acid ratios respectively increase or decrease beyond 5% of reference diets. To reflect the non-linear trends in growth or nutritional content with replacement across different studies, we fitted smoother-spline mixed-effects models to data on feed conversion and n3:n6 fatty acid ratios from 0 to 100% fishmeal or oil replacement (or the maximum used in the feeding trial) using the sme R package (Berk 2018). As we are interested only in relative rather than absolute changes to both these parameters, we modelled replacement effects on relative feed conversion or fatty acid ratios for study *i* as a smooth function of forage fish replacement, $y_i(r)$:

$$y_i(r) = \mu(r) + v_i(r) + \epsilon_i(r) \qquad \text{Eq. 2}$$

Where $\mu(r)$ is the mean function across all studies, $v_i(r)$ is study *i*'s deviation from the mean function assumed to also be a smooth function of replacement, and $\epsilon_i(r)$, the error process (Berk 2018). Using the study ID as the random effect, we capture combined information on the experimental species, specific forage fish substitute, and amino acid and enzyme supplementation regimes used, which would otherwise be highly collinear.

Smoother-spline mixed-effects (SME) models are ideally suited to our dataset due to small sample sizes, noisy observations, irregular measurements, and missing data inherent from pulling independently designed experimental research together. To avoid the constraints small sample size imposes on the number and locations of knots between polynomials within smoother splines, SME models use every measured replacement percentage point as a knot and introduce penalty parameters for lack of smoothness to avoid overfitting. We estimate these penalty parameters during model fit using the corrected Akaike Information Criterion (AICc), maximising penalised likelihood. Knot number and location were occasionally manually fitted, however, if there were fewer observations than degrees of freedom when using the default approach outlined above. Manual fitting was honed through diagnostic checks of quantile-quantile plots and the spread of standardised residuals across forage fish replacement values and fitted values for relative feed conversion or n3:n6 fatty acid ratios. By plotting model outputs, we discern where (in terms of forage fish replacement levels) clear increases in feed conversion ratio occur when 95% confidence intervals rise more than 5% above feed conversion ratios of reference diets. We repeat this for where confidence intervals fall more than 5% below n3:n6 ratios for reference diets under fish oil replacement.

Finally, we combine these thresholds as limits of plausible fishmeal or oil replacement with apparent trade-offs in the dietary change of the opposite ingredient, i.e. for species *i* under a fishmeal replacement regime from feed *k:*

$$FMFO_{i,k} = \sum\left(FMFO_i \cdot \Delta FM_{(opt)i,k}\right) + \left(FMFO_i \cdot \Delta FO_{(opt)i,k}\right) \qquad \text{Eq.3}$$

Where $FMFO_{i,k}$ = proportional dietary contribution of fishmeal and oil, $\Delta FM_{(opt)}$ = optimal proportional replacement level of dietary fishmeal and $\Delta FO_{(opt)}$ = proportional change in fish oil associated with $\Delta FM_{(opt)}$ or vice versa. This can then be reinserted into the forage fish calculation (Eq.1):

$$FF_{i,j} = Prod_{i,j} \cdot Prop_i \cdot FCR_i \cdot FMFO_{i,k} \cdot Cv$$

Applying these combined results to dietary information within forage fish demand calculations for 2030, we assess the potential for each novel feed type to keep forage fish demands of fed aquaculture below historical supply.

Chapter 4

4. Food production shocks across land and sea

This research in this chapter has been published as:

Cottrell, R.S., Nash, K.L., Halpern, B.S., Remenyi, T.A., Corney, S.P., Fleming, A., Fulton, E.A., Hornborg, S., Johne, A., Watson, R.A. and Blanchard, J.L., 2019. Food production shocks across land and sea. *Nature Sustainability*, *2*(2), p.130.

See Appendix F for the PDF of this published article. It is presented here in its published form but formatted for the purpose of this thesis.

4.1. Abstract

Sudden losses to food production (that is, shocks) and their consequences across land and sea pose cumulative threats to global sustainability. We conduct an integrated assessment of crop, livestock, aquaculture, and fisheries production data to understand how shocks occurring in one food sector can create diverse and linked challenges among others. We show that some regions are shock hotspots, exposed frequently to shocks across multiple sectors. Critically, shock frequency has increased through time on land and sea at a global scale. Geopolitical and extreme-weather events were the main shock drivers, although with considerable differences across sectors. We illustrate how social-ecological drivers, influenced by dynamics of the food system, can spillover multiple food sectors and create synchronous challenges or trade-offs among terrestrial and aquatic systems. In a more shock-prone and interconnected world, social protection mechanisms that help people anticipate, cope and recover from losses may be central to sustainability

4.2. Introduction

Food production shocks pose significant challenges for the UN Sustainable Development Goals (SDGs) (United Nations 2015a) because of their potential to disrupt food supply and security, livelihoods, and human well-being (Jessica A Gephart et al. 2017, Seekell et al. 2017, FAO IFAD UNICEF WFP & WHO 2017, Tadesse et al. 2014, Marchand et al. 2016, Sasson et al. 2012, Buhaug et al. 2015). A range of social-ecological pressures on food systems can drive shocks to production through direct or indirect mechanisms. Drought or flooding can increase mortality in crops, livestock, or farmed fish; whereas violent conflict may prevent farmers or fishers accessing their production systems. Prolonged overfishing can also produce sudden losses in catch as exploited fish populations are pushed toward ecological tipping points, after which we see stock collapse. Understanding national vulnerabilities to sudden production losses requires a complete picture of shock exposure across sectors on land and sea given the large differences in dependence on agricultural and seafood sectors worldwide (Fisher et al. 2017, Blanchard et al. 2017). Yet studies on food production shocks to date largely deal with agricultural and seafood commodities in isolation (Jessica A Gephart et al. 2017, Sartori & Schiavo 2015, Buhaug et al. 2015). Integrated understanding is required to assess cumulative risks to sustainability across all food sectors in the face of environmental change and human population growth.

We investigate historical global trends in exposure to and drivers of food production shocks across multiple sectors (crop, livestock, fisheries, and aquaculture). We use an established, standardised approach to identify shocks and their drivers, and map their global frequency and co-occurrence. We highlight the different ways shocks can permeate or drive trade-offs across multiple food production sectors. In doing so, we reveal how links among agriculture, aquaculture and fisheries production can result in diverse outcomes for food production and sustainability.

4.3. Results and Discussion

4.3.1. Global trends in food production shocks

From 741 available time series (crops = 187, livestock = 190, fisheries = 202, aquaculture = 162) we detected 226 production shocks from 1961 – 2013. When pooled, we found agricultural sectors (crop and livestock) slightly more shock prone than aquatic sectors (fisheries and aquaculture) over the 53-year period (0.31 vs 0.29 shocks country^{-1} respectively). Shock frequencies were regionally distinct within sectors, with some areas experiencing shocks far more frequently than others (Figure 13). Shock frequencies were highest in South Asia for crops (Figure 13a), the Caribbean for livestock (Figure 13b), Eastern Europe for fisheries (Figure 13c), and South America for aquaculture sectors (Figure 13d). Importantly, some regions experienced high frequency in more than one sector. For example, South Asia experienced one of the highest shock frequencies to livestock as well as to crops, and the Caribbean experienced high frequency of fisheries shocks alongside livestock systems. Therefore, while there is varying exposure to production shocks within sectors, in several regions these patterns overlap and create areas of high exposure to production shocks across multiple fronts.

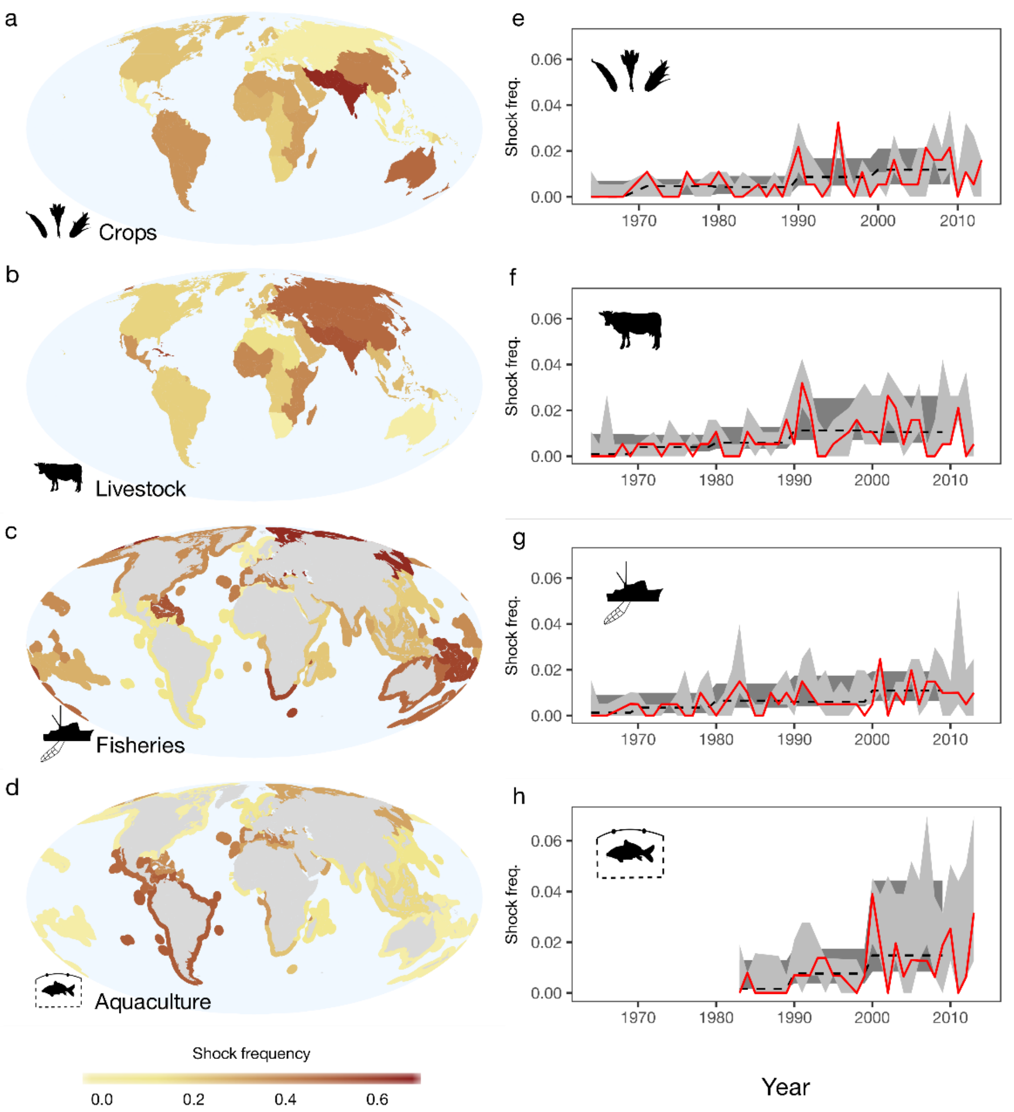

Figure 13 – Spatial (a-d) and temporal (e-g) trends in food production shock frequency in crop, livestock, fisheries, and aquaculture sectors from 1961-2013. Regions include North America, Central America, Caribbean, South America, Northern Europe, Western Europe, Southern Europe, Eastern Europe, North Africa, West Africa, Central Africa, Southern Africa, East Africa, Western Asia, South Asia, East Asia, South-east Asia, Melanesian, Micronesia, Australia and New Zealand, and Polynesia. The red line in the time series indicates the annual shock frequency from the shocks identified in this study. Light grey confidence interval describes the plausible range of frequencies under different combinations of LOESS model span (0.2-0.8), production baseline durations (3,5,7, or 9

years) and average types used for baseline (mean or median). Dashed black line is the decadal mean of the red line and the dark grey band is the decadal minima and maxima of the confidence interval.

The frequency of shocks has increased across all sectors at a global scale. In our results, annual shock frequencies fluctuated considerably over time, yet decadal averages, minima and maxima increased steadily from the 1960s and 70s (Figure 13e-h). We did not detect any shocks to aquaculture production until the early 1980s likely due to its nascence, but decadal shock rates have risen faster and to a level higher than in any other sector since (Figure 13h). Increasing shock frequency is a food security concern in itself. Conflict-related shocks across Sub-Saharan Africa and the Middle East since 2010 are responsible, combined with adverse climate conditions, for the first uptick in global hunger in recent times (FAO IFAD UNICEF WFP & WHO 2017). While the human impact of shocks depends on the degree to which livelihoods in a region or country depend on food production and the variation in vulnerability among households (FAO IFAD UNICEF WFP & WHO 2017), increased frequency reduces time for recovery between events. Smaller windows for recovery hinder coping strategies such as the accumulation of assets that can be sold during times of hardship, and can ultimately negatively influence the resilience of producers and communities to shocks (FAO IFAD UNICEF WFP & WHO 2017).

4.3.2. Drivers of production shocks across land and sea

Extreme weather events and geopolitical crises were the dominant drivers of shocks in our analysis but the relative importance of drivers varied across sectors (Figure 14). Over half of all shocks to crop production systems were a result of extreme weather events (Figure 14), largely drought, reinforcing the concern about vulnerability of arable systems to climatic and meteorological volatility across the globe(Lesk et al. 2016). We also found extreme weather to be a major driver of shocks to livestock (23%), particularly where reductions to feed occurred. For instance, severe summertime droughts in Mongolia in 2001 and 2010 reduced fodder and feed availability, compromised livestock condition, and led to mass mortality events during cold winter extremes(Rao et al. 2015). Diseases such as foot and mouth also contributed to 10% of livestock shocks. Geopolitical crises, however, such as economic decentralisation in Europe or conflict in Sub-Saharan Africa, accounted for the greatest proportion (41%) of the livestock shocks in our analysis (Figure 14).

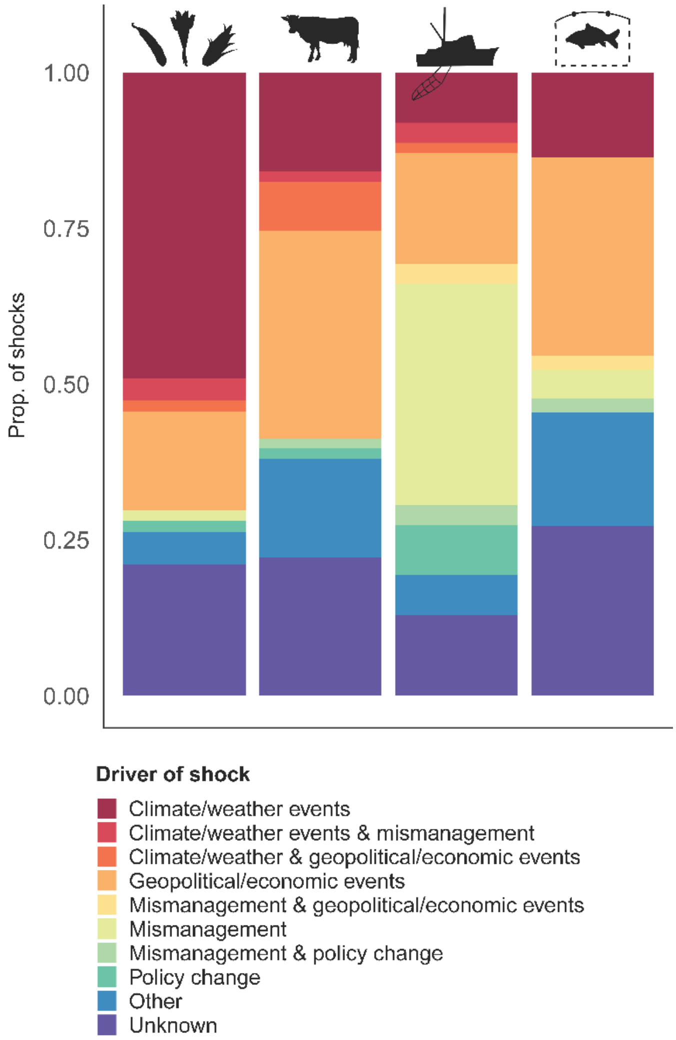

Figure 14 – Drivers of food production shocks for crop, livestock, fisheries and aquaculture sectors.

In contrast, drivers of seafood production shocks were more diverse than for terrestrial systems (Figure 14). For fisheries, overfishing was responsible, at least in part, for 45% of shocks detected in landings data. However, geopolitical crises contributed to 23% of fisheries shocks, climate/weather events to 13% and policy changes to 11%. Shocks driven by policy changes can reflect positive interventions, but may also be a response to declining resources. In the aquaculture sector, while disease (included in '*Other*' category) was the most common individual driver, responsible for 16% of shocks overall, a spectrum of geopolitical stressors were behind a third of aquaculture shocks, from state dissolution, to violent conflict, and declining competitiveness in export markets (FAO 2003, Kimenyi et al. 2014, FAO 2005a).

Patterns of driver influence differed across regions (Appendix Figure 6). For example, in South Asia, where agricultural shocks were most frequent, nearly all crop and livestock losses were driven by flood or drought. Whereas in Sub-Saharan Africa, where the greatest burden of hunger still persists (FAO IFAD UNICEF WFP & WHO 2017), geopolitical or economic crises were the leading drivers of agricultural shocks (Appendix Figure 6). In seafood sectors, regional diversity of driver types was more consistent. In wild systems, overfishing and geopolitical drivers contributed to numerous shocks across Europe, Sub-Saharan Africa and East Asia. For aquaculture, disease was the primary driver in Europe and Latin America, but geopolitical conditions were more significant for both East Asia or the Middle East and North Africa (Appendix Figure 6). Therefore, while we highlight dominant shock drivers for each sector at a global scale, we reiterate that challenges for increasing food production will vary greatly from place to place.

The reason for the increase in shock frequency through time across sectors is not clear, in part because many potential factors (including quality of reporting) have changed and increased over the time period. However, crop production shocks driven by extreme weather became more frequent in our results over time (Appendix Figure 7). In livestock, fisheries and aquaculture sectors particularly, the diversity of drivers increased from the 1970s (Appendix Figure 7). As food systems become increasingly globalised and interdependent, a greater diversity of exogenous shocks may influence them over time (Liu et al. 2013). For instance, livestock disease is increasing globally, driven largely by a rapid rise in demand for meat, the incursion of livestock in natural systems, intense farming practices and the mass movement of animals and people (Perry et al. 2013). The nature of interdependencies among sectors are also changing. Demands for feed now tightly couple aquaculture to both capture fisheries and crop systems (Froehlich, Runge, et al. 2018), and the production challenges each of these encounter. Furthermore, financial institutions motivated by socioeconomic drivers disconnected from their geographies of influence, increasingly sway producer investments and decisions with complex or unknown consequences for production stability or sustainability (Galaz et al. 2015). .

4.3.3. Co-occurrence and spillover across terrestrial and aquatic sectors

Climate events, violent conflict or other social-ecological stressors can create complex synchronous, or lagged effects across different systems (FAO IFAD UNICEF WFP & WHO 2017). Therefore, a single stressor could elicit numerous shocks across different food sectors but not always at the same time. So while we would not necessarily expect shocks from the same stressor to coincide at the exact shock point (year), we would assume to see clumping of shocks within broader time-periods. Co-occurrence appeared in our data from the early 1990s and more frequently in the latter half our time-series (Figure 15a). Of the 134 nations affected by shocks in our analysis, 22 of these experienced shocks in multiple sectors during the same five-year period (Figure 15b). We recognise these trends are influenced by the size of bins used and further do not reflect changes in other sectors not detected as a shock (although they may be a response or a driver of shocks detected here). Overlapping shock occurrence in this way allows us identify and further examine the more detailed conditions underpinning occurrence of multi-sectoral shocks.

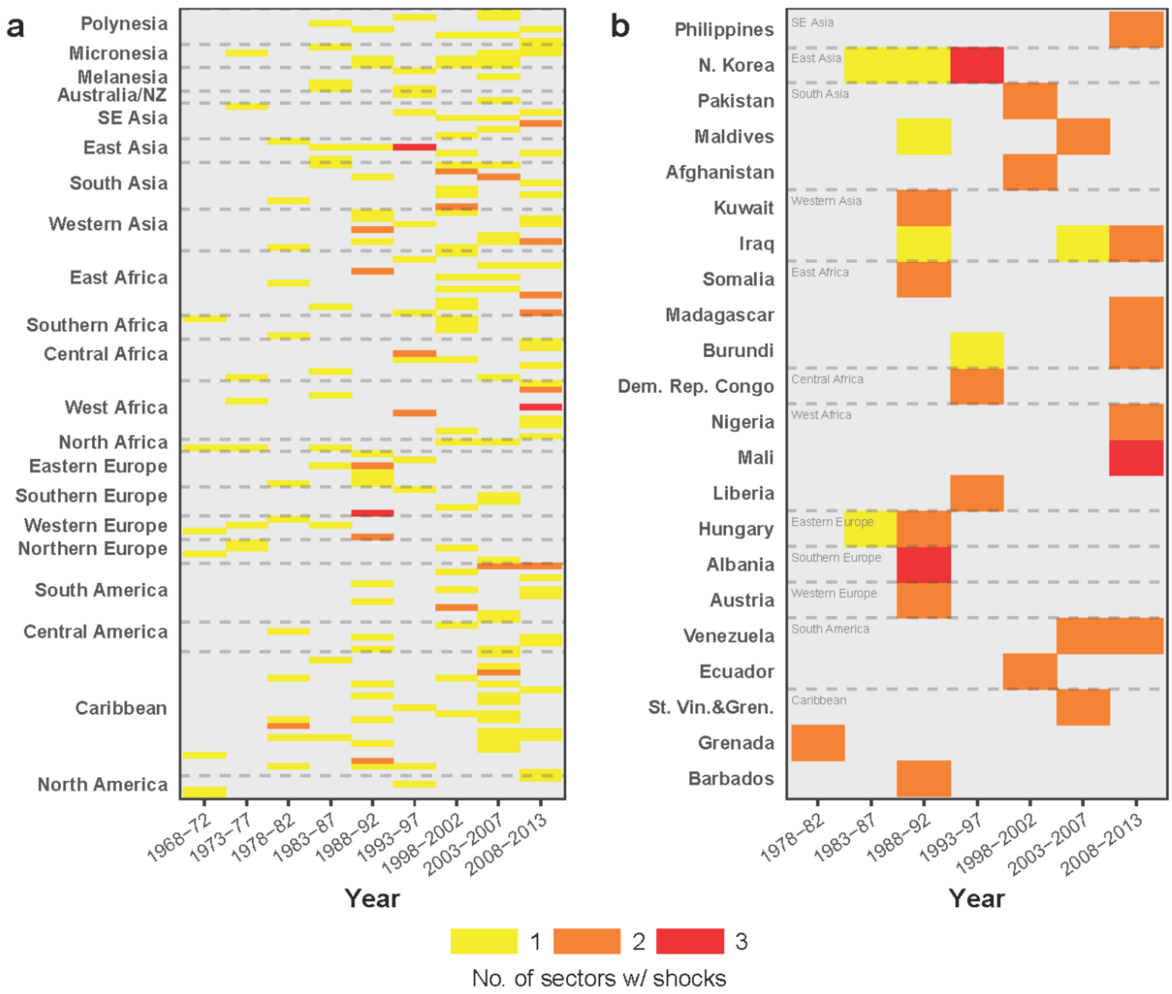

Figure 15 – Heat map of shock co-occurrence across terrestrial and aquatic food sectors through time. a) Global extent of co-occurrence in all countries affected by shocks in our analysis grouped by subregion b) Isolated countries where shocks occurred across multiple sectors during the same five-year period.

Shocks spanning multiple sectors were often driven by geopolitical events. For example, loss of Soviet-linked subsidies, and reduced export markets in Albania during the fall of communism resulted in large declines in crop, fisheries, and aquaculture production (FAO 2005b, Moutopoulos et al. 2015, FAO 2015). North Korea experienced lagged impacts from economic fall-out from USSR dissolution by the mid-1990s, and extreme flooding exacerbated the scale of production losses on land. The resulting famine led to the deaths over 200,000 people (Noland 2004, Noland et al. 2001). In Mali, internal conflict from 2011 onwards displaced farmers and fishermen alike by limiting access to rivers and farms directly, or through disruption to supply chains (Kimenyi et al. 2014). Nonetheless, the geography of the shock, the magnitude of the driver, the importance of the affected systems for national production, and the adaptive (e.g. coping strategies), absorptive (e.g. reserves, assets, capital), or transformative capacities (e.g. governance mechanisms) (FAO IFAD UNICEF WFP & WHO 2017) of affected communities will all influence how a shock manifests across different food system. Taking further examples from Figure 15, we illustrate how the social-ecological dynamics of both the country and the shock can yield variable responses across sectors (Figure 16).

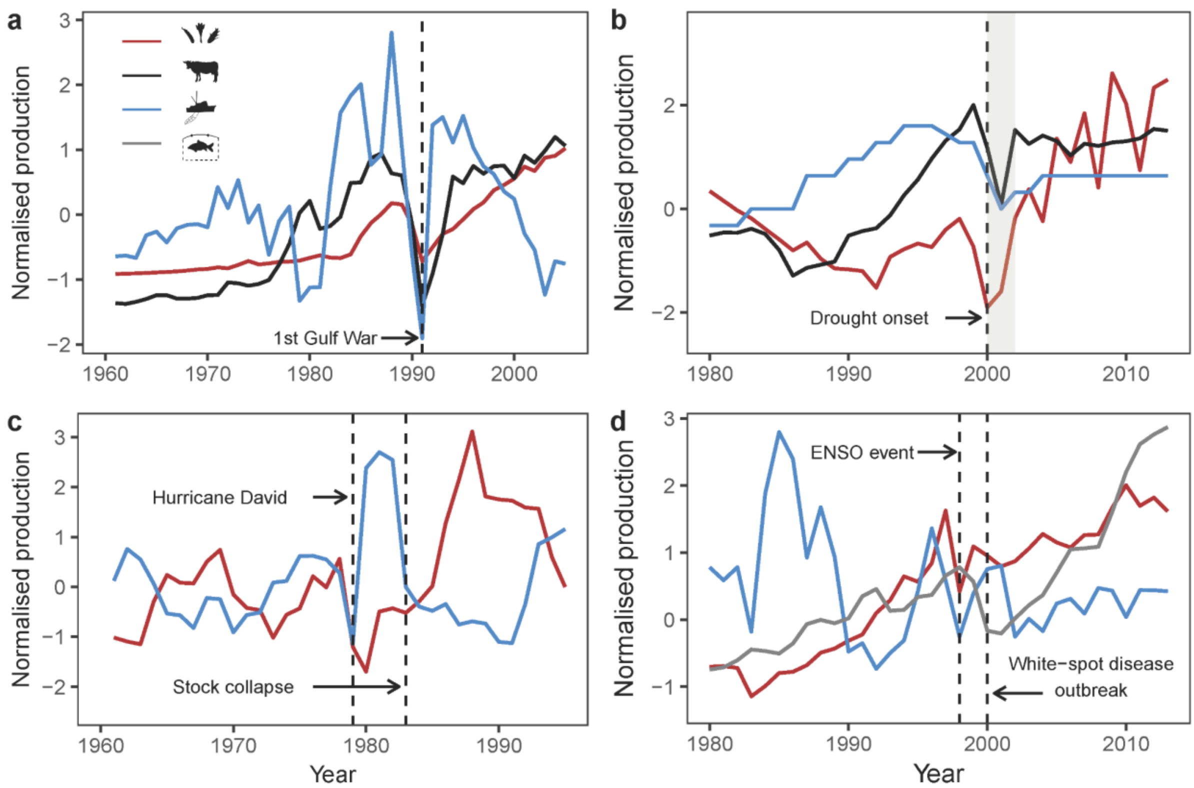

Figure 16 – Case studies of shock spillover, trade-offs, and co-occurrence across terrestrial and aquatic sectors. a) Invasion of Kuwait during the Gulf War b) Severe drought in Afghanistan c) Land-sea switches following Hurricane David in Dominica d) El-

nino driven floods on land followed by an outbreak of white-spot disease in shrimp farms, Ecuador.

Drivers of shocks can create similar or opposing responses in production across multiple sectors, revealing links between terrestrial and aquatic systems. In both Kuwait (Figure 16a) and Afghanistan (Figure 16b), different shock drivers at different scales created similar national-level responses spanning terrestrial and aquatic production. The invasion of Kuwait by Iraq in late 1990 and the subsequent conflict with the US and allies was a huge nationwide disturbance, caused widespread devastation to agricultural land and the removal of the majority of Kuwaiti fishing vessels ceased commercial fishing (Matthews 2014). Rapid declines in crop, livestock and fisheries production occurred from 1990, with shocks detected in both livestock and fisheries time-series (Figure 16a). In Afghanistan, a severe drought from 2000 – 2002 decimated cereal production particularly in the country's north. Large increases in animal diseases and reduced fodder severely affected production for pastoralists(FAO 2002) and we detected a shock to fisheries landings at the same point (Figure 16b). The similar declines across sectors disguise the differences in vulnerability however. Disturbances at the scale of the Gulf War are rare events, whereas droughts are frequent across Western Asia. In Afghanistan, its landlockedness and the absence of marine fisheries leaves national food production more vulnerable to drought.

In contrast, divergent responses to extreme weather in Dominica illustrate the potential for land-sea trade-offs when human adaptation measures shift resource use across sectors. Repeated damage to farmland from tropical storms during the 1970s pushed more of the nation's farmers into fishing for a primary income source (Ramdeen et al. 2014). After Hurricane David decimated the banana crop in 1979, fisheries landings increased dramatically from 1980, followed by a rapid decline in 1983 (Figure 16c)**,** likely driven by overfishing leading to stock collapse in nearshore waters (Ramdeen et al. 2014). Shifts between land and sea following a shock were rare in our analysis of national time series. It is possible Dominica's small size, and high dependence on a single crop for livelihoods of the rural poor (who have few absorptive strategies for coping with crises) (Mohan 2017), contributed to this response. However, it is likely these switches occur much more widely at smaller scales given the prevalence of joint dependence on fisheries and agriculture worldwide (Fisher et al. 2017) and because small-scale fisheries are often use to buffer the effects of extreme events (Belhabib et al. 2018).

In Ecuador, shocks occurred at similar points in both crop and aquaculture systems with seemingly unrelated proximate drivers if investigated solely from single sector perspectives (Figure 16d). The strong El-Nino Southern Oscillation (ENSO) event of 1998 led to widespread flood damage to croplands across Ecuador (Bayer et al. 2014) detected as a shock in our time-series, and at the same time, a large reduction in coastal fisheries landings occurred (Figure 16d), although not detected as shock due to the variable nature of the Humboldt system (Jessica A Gephart et al. 2017). While there were reports of flood damages to shrimp farms in 1998, two years later we detected a shock to aquaculture production because of dramatic declines in the shrimp industry. These declines are consistent with the reports of a white-spot syndrome outbreak, which severely affected the industry in 2000 (FAO 2005c). We could find no documented link of the El-Nino event and the disease outbreak; however, abnormally warm coastal waters on the Pacific South American coast are associated with both El-Nino events and the rapid spread of the White-spot Syndrome virus (Lafferty et al. 2015). Irrespective of whether these shocks are connected or not, an increased co-occurrence because of linked or independent drivers becomes problematic for communities with a reduced capacity to deal with these dual impacts.

4.3.4. Challenges and potential for sustainable development in a shock-prone world

Shocks across multiple sectors pose significant threats to improving global food security as well as other sustainability targets. For example, one target within SDG 2 of zero hunger, aims to strengthen adaptive capacity in the face of climate change and extreme events (United Nations 2015a). For many people, livelihood diversification between agriculture and fisheries is a key strategy in alleviating the impacts of production shortfalls (Allison & Ellis 2001, van Ginkel et al. 2013, Fisher et al. 2017) yet shocks across multiple sectors compromise these options. A lack of viable alternatives can drive people to derive food or income from other sources with unpredictable sustainability consequences. The declines in large mammal populations in West Africa during times of low fish supply or after the collapse of agricultural systems in the Soviet Union are clear examples (Brashares et al. 2004, Bragina et al. 2015). Trade-offs across sectors like this including the example from Dominica (Figure 16c) present significant challenges for achieving other sustainability targets. Unpredictable shifts among sectors create interactions among the goals for life on land, life below water or responsible production and consumption (United Nations 2015a) for instance. Further, as shock rates increase across all sectors the capacity for shocks to co-occur increases simultaneously.

On a global scale, increased shock frequency may pose a threat to the resilience of the global food system through impacts on trade. Nearly a quarter of food, agricultural land, and freshwater resources are accessed through trade (Marchand et al. 2016) and a number of countries are dependent on imports to meet the food demands of their population (Suweis et al. 2015). Trade dependency is also becoming more regionally specialised, with some major breadbaskets the sole suppliers of commodities to other nations. For example, Thailand currently provides over 96% of rice imports to a number of West African countries (Puma et al. 2015). The high dependence on just a handful of producers for some countries highlights future vulnerability. Producing countries often reduce or ban exports during production crises to protect domestic supply, endangering import-dependent trade partners (Marchand et al. 2016, Tadesse et al. 2014, Suweis et al. 2015, Puma et al. 2015). If shock frequencies continue to increase and major producing nations are affected, a shift to a state of reduced exports is plausible at a global level. Increased commodity prices linked to global scarcity would favor higher paying nations (Puma et al. 2015), leaving low-income, trade-dependent countries in jeopardy. In the case that a higher frequency of shocks is influencing the stability of trade, we might expect to see increased temporal variability in either trade or price data. Whether or not these signals are present in the available data warrants further investigation.

To build resilience in shock-prone areas, a number of social protection mechanisms will likely be of increasing importance to help nations, communities and households prevent, anticipate, cope with and recover from shocks (FAO IFAD UNICEF WFP & WHO 2017). Conflict-related shocks remain the biggest barrier to food security in the world's most food insecure regions (FAO IFAD UNICEF WFP & WHO 2017, Buhaug et al. 2015) Greater understanding of the proximate and ultimate causes of conflict in different areas will be central to prevention (FAO IFAD UNICEF WFP & WHO 2017). Development of novel early-warning systems for violence are already underway (Uppsala Universitet 2017). Timely food and cash transfers, and food or cash for work programmes during times of crisis show promise throughout Sub-Saharan Africa (Devereaux 2016). Participatory planning with, and post-conflict support for, those displaced such as provisioning of tools, seeds or skills training will be crucial in building faster recovery times and closing yield gaps (FAO IFAD UNICEF WFP & WHO 2017, Khan et al. 2014). In aquaculture, increases in open data and new sequencing technologies to help understanding of the microbial conditions surrounding disease emergence, will be fundamental to meeting increasing global seafood demands (Stentiford et al. 2017, Stentiford et al. 2012). Weather-indexed insurance is another innovative tool that may help protect producers against income or food access losses during adverse conditions (Hazell & Hess 2010), and will be particularly important if predictions of more frequent extreme events are further realized (Cai et al. 2014).

Trends discussed here will almost certainly underrepresent the frequency of production shocks due to aggregation of production data to country level. Sudden production losses may be locally isolated or restricted to a single food type but are still of concern for livelihoods and food security in affected communities. Summing across commodity types tends to smooth out shocks to single food items – particularly in North America where food is grown over such a large and diverse landscape. We also acknowledge that those in the know may have expected some shocks described here, although to what extent is unclear. While this is a limitation of statistical detection in production time-series, this method does allow non-biased detection of shocks caused by drivers with scant data (e.g. sudden declines from fish stock collapse). Although sensitivity analyses of Cook's distance, LOESS span or production baseline parameters provided confidence intervals, we may not have detected all shocks (Appendix Figure 8). Further, the shock detection method described here is less sensitive to production changes in highly variable systems where large fluctuations are common within the time series (Jessica A Gephart et al. 2017). Moreover, while shocks remain a significant barrier to food security in many regions, this method does not account for gradual declines in food production, such as those expected to productivity under climate change (Blanchard et al. 2017), which may be more damaging overall.

Food production shocks can negatively influence food security, particularly if terrestrial and aquatic systems are simultaneously affected. Achieving the SDGs by 2030 will require addressing the underlying drivers of, or threats from food production shocks. With shock frequency increasing across sectors through time, the likelihood of shock co-occurrence increases, particularly in shock-prone regions such as the Caribbean or South Asia. Production challenges across multiple sectors will be hardest felt by those with lower capacity to adapt to or absorb shocks. With extreme weather events predicted to increase into the future, potentially interacting with civil unrest, achieving food security in the most exposed regions may hinge on successful social protection mechanisms to help people cope and recover. Integrating and understanding links between land and sea will be critical for programmes and research aiming to affect progress towards food security and sustainable development.

4.4. Methods

To identify and compare shock occurrence among fundamentally different systems (agriculture and seafood), we adopt the paired statistical and qualitative approach of Gephart et al (Jessica A Gephart et al. 2017). This method identifies shocks through breaks in the autocorrelation structure of a time-series and combines this with a literature search for likely driver of the shock. Alternative studies have used pre-published data sets on extreme events to understand responses in production data(Belhabib et al. 2018), however this skews focus toward drivers with plentiful data – often terrestrial and biophysical events such as floods, droughts, or cold fronts. Others have also used the trade in virtual water to study shocks in agricultural systems (Sartori & Schiavo 2015), but this largely eliminates the marine component of our food system. Reliance on statistical detection in production data avoids specificity making it a standardised approach applicable across crop, livestock, fisheries, and aquaculture sectors.

4.4.1. Data Sources

We use a range of food production data from the UN's Food and Agricultural Organization (FAO) combined with published production datasets for our analysis. We used crop and livestock data from FAOSTAT production quantity dataset 1961 – 2014 dataset (http://www.fao.org/faostat/en/) (FAO 2019a). Crop types included cereals, coarse grains, fruits, roots and tubers, pulses, tree nuts and vegetables; while livestock included total meat, milk, and egg production from bovine, poultry, swine, mutton and goat sources. We used the FAO FishStat database (FAO 2019b) for inland and marine aquaculture production, and inland fisheries landings data (1950 – 2015 Global Production dataset, www.fao.org/fishery/topic/166235/en.). We used marine fish landings data from Watson (2017) to account for estimates of large-scale, small-scale and illegal, unregulated, and unreported (IUU) landings. Fisheries data included all landed finfish, crustaceans, and molluscs. Aquaculture data included all farmed finfish, crustaceans, molluscs and algae. While we recognise that underreporting of small-scale production across all sectors is a limitation of FAO data, it provides global coverage of production across multiple sectors, and the detection of shocks relies on overall trends in data rather than absolute production values.

4.4.2. Detecting shocks and identifying drives

For all countries we aggregated production to total annual values from 1961 – 2013 across all commodity types described above for crop, livestock, fisheries and aquaculture sectors. We fitted local polynomial regression (LOESS) models with a span of 0.6 to aggregated annual production data for all countries and sectors. We regressed model residuals against lag-1 residuals, and any outliers in this regression (quantified as data points with a Cook's distance > 0.3), we deemed shocks (Appendix Figure 9). Given only production losses are of concern for food security, we only considered shock points associated with a loss in production relative to a previous 7-year median production baseline.

Consistent with the approach by Gephart et al.(Jessica A Gephart et al. 2017), for each shock detected we calculated the size of a shock and its recovery time for comparisons across sectors and regions (Appendix Figure 6). Shock size equals the loss in production (in tonnes) relative to the previous 7-year median baseline. Recovery time for the shock is calculated as the number of years taken to increase back up to at least 95% of this baseline. Some shocks did not recover by the end of the time series and we highlight the individual shocks in Appendix Table 6. We calculated shock frequencies for each geographical region, by dividing the number of shocks detected from 1961 – 2013 by the number of time-series used for detection. For annual shock frequencies, for every sector we divided the number of shocks detected for a given year by the number of countries producing in that year. This approach compensates for different numbers of countries within each region, and the increasing number of countries producing through time.

Adopting a qualitative approach to identifying the drivers of production shocks helps account for and recognise the multiple and complex social-ecological factors contributing to an event. For a detected shock, we searched peer-reviewed and grey literature (e.g. NGO reports, news articles etc.) for the likely causes, or drivers, of each individual shock. Each shock was assessed independently disaggregating production data into individual commodities to identify the species affected and check our analysis, which allowed greater specificity to our search. We only attributed a driver to a shock when our search returned a documented event or set of conditions where a negative effect on agricultural or seafood sectors (dependent on the sector affected) was explicitly mentioned at or just before the shock point (i.e. documentation stipulated the link rather than us establishing purely correlative trends). The combination of quantitative and qualitative methods adopted by Gephart et al. (2017b) provide complimentary approaches where purely data driven methods may highlight correlative relationships with drivers without causation. Likewise, purely qualitative analyses may be limited in their capacity to detect shocks because of differences in reporting across regions. We caution that this approach is not meant to provide a comprehensive list of contributing factors for a given shock within the data, but instead highlights potential drivers of change from the literature we identify. It is plausible that other unidentified factors contribute to the changes seen in the data.

In our analysis, we classify drivers of shocks into five main categories. *Climate/weather events* include anomalies such as storms, droughts, ENSO events, or climate-driven ecosystem change. *Geopolitical/economic events* covers disturbances from conflict, state dissolution or financial crises. *Mismanagement* includes multiple categories such as overfishing in the ocean, or deforestation and erosion of soils on land. *Policy change* can refer to, for example, closure of a fishery or abolition of agricultural subsidies. The '*Other*' category includes a wide range of pressures from production diseases to geological events such as tsunamis or volcanic eruptions. Due to the complex nature of social-ecological stressors on food systems, we combined many of these categories to explain the drivers of production shocks, and highlight these sub-categories**.** The Unknown category contains shocks for which we could not find a documented reason. It is possible that our statistical approach to detection means we identify changes to national reporting methods as a shock. This highlights the importance of the complimentary quantitative and qualitative approaches used here to identify if a statistical anomaly in production data is reflected by conditions or events reported in reality (Jessica A Gephart et al. 2017).

4.4.3. Data availability

Crop and livestock production data were accessed through FAOSTAT http://www.fao.org/faostat/en/. For marine fisheries production we used the published dataset by Watson (Watson 2017) at https://www.nature.com/articles/sdata201739. Aquaculture and inland fisheries data were extracted from global production datasets using FishStat software (www.fao.org/fishery/topic/166235/en). All code and data products used for analyses in this study will be made publicly available through Github (linked provided on manuscript acceptance).

Chapter 5

5. Addressing land-sea shifts in Australian consumption for food system sustainability

This chapter has been prepared for journal submission. The contributing authors are:

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5.1. Abstract

Food consumption patterns can drive shifts in the partitioning of human resource use across land and sea. Knowledge of where food is consumed and produced is needed to understand environmental impacts and inform sustainable development policies. Here, we investigate whether there are land-sea shifts in Australian food consumption patterns. By synthesizing and analysing national food production, consumption, and trade data for Australia, with data on seafood public perceptions and supply chain sustainability, we show that fish is taking a greater share of food consumed in Australia. Current deficits in national seafood production displace the impacts of Australian seafood demand onto trade partners, creating challenges for sustainability of imported seafood and responsible consumption goals. Our early warning signal analysis of capture fisheries landings suggests wild production limits have been reached under current management. Therefore, we outline how domestic aquaculture growth will be increasingly important to fill the widening consumption-production gap. Poor public perceptions of aquaculture limit growth in the most important production regions, but we show how positive perceptions elsewhere coupled with huge potential for diversification in farmed species, ecosystem approaches to production, and offshore growth may help overcome these constraints in the future. Whether increased volatility on land could further shift the pressures of animal production onto marine food systems needs further investigation.

5.2. Introduction

Food systems and their influence on human and environmental wellbeing lie at the heart of the United Nations Sustainable Development Goals (SDGs) (United Nations 2015a). Agriculture, fisheries, and aquaculture play important roles in human nutrition and livelihoods – central components to alleviating poverty (SDG1) and eradicating global hunger (SDG 2)

(FAO IFAD UNICEF WFP & WHO 2019). Yet terrestrial and aquatic food production systems are major drivers of natural ecosystem degradation, biodiversity loss, and climate change, paradoxically undermining their function (Springmann et al. 2018, Worm et al. 2006, Campbell et al. 2017). These tensions highlight potential trade-offs and feedbacks within and among the social and environmental dimensions of sustainability as we strive to meet increasing total and per-capita demands for food. Thus, encouraging growth in food systems that help meet future food demands, produce healthy food, and promote resilient livelihoods, while minimizing the environmental impact of production should be prioritized in national food policy, planning, and consumption.

Food consumption patterns are changing around the globe. As we become wealthier, demand for a greater variety of food increases with a greater proportion coming from animal-based products (Tilman & Clark 2014, Godfray et al. 2018). Such transitions pose several sustainability challenges. Typically, diets high in animal products account for far greater greenhouse gas and acidifying emissions, land use, nutrient pollution, and freshwater use compared to plant-based diets because of inefficient transfer of energy from primary producers through to the animals we consume for food (Bonhommeau et al. 2013, Godfray et al. 2018, Hilborn et al. 2018, Poore & Nemecek 2018, Gephart et al. 2016, Willett et al. 2019). More resource-intensive diets are also closely linked to malnutrition and declines in human health; greater consumption of refined sugars, fats, oils, and meat are linked to increased incidence of obesity, coronary heart disease, type II diabetes, and cancer for example (Tilman & Clark 2014, Willett et al. 2019). Further, while total and per-capita meat and fish consumption have increased globally (Tilman & Clark 2014, FAO 2018), these trends do not always parallel each other at a national level, with meat consumption proportionally replacing fish in many countries, or fish consumption taking a greater share in others (Nam et al. 2010, FAO 2018). Thus, like shocks to production in one food system can displace pressure from human resource use into another (Cottrell et al. 2019, Gephart et al.

2017), creeping changes to consumption can produce similar albeit more sustained shifts across the land-sea divide.

Using Australia as a case study, we synthesize and analyze diverse data sources to investigate the sustainability implications of land-sea shifts in consumption and explore the challenges towards addressing such displacement through trade and production pathways. We use national food production, and consumption data to understand how consumption patterns are shifting resource use across terrestrial and aquatic systems. We then explore and compare the social and environmental implications of potential solutions through using data on domestic production, trade, supply chain sustainability metrics, and public perceptions to understand the best route toward more responsible production and consumption (SDG 12).

5.3. Results and Discussion

5.3.1. Changing consumption patterns in Australia

Australia's per capita consumption of animal foods (meat, eggs, milk, fish) is one of the highest in the world (14th of 167 countries for total animal foods, 1st for meat; Appendix Figure 11; FAO (2019a)). However, relative contributions of various food items to Australian consumption trends have shifted considerably through time. While meat and fruit and vegetables have increased by approximately 10% and 40% between 1960 and 2013 respectively, milk consumption has decreased by between 5 and 10%, cereals by almost 20% and egg consumption has nearly halved (Figure 17a). In contrast, fish and seafood consumption has over doubled in the same period, taking a greater share of total food supply and approaching 20% of animal meat consumption (Figure17 a,b), increasingly shifting the pressure from food demands across the land-sea interface.

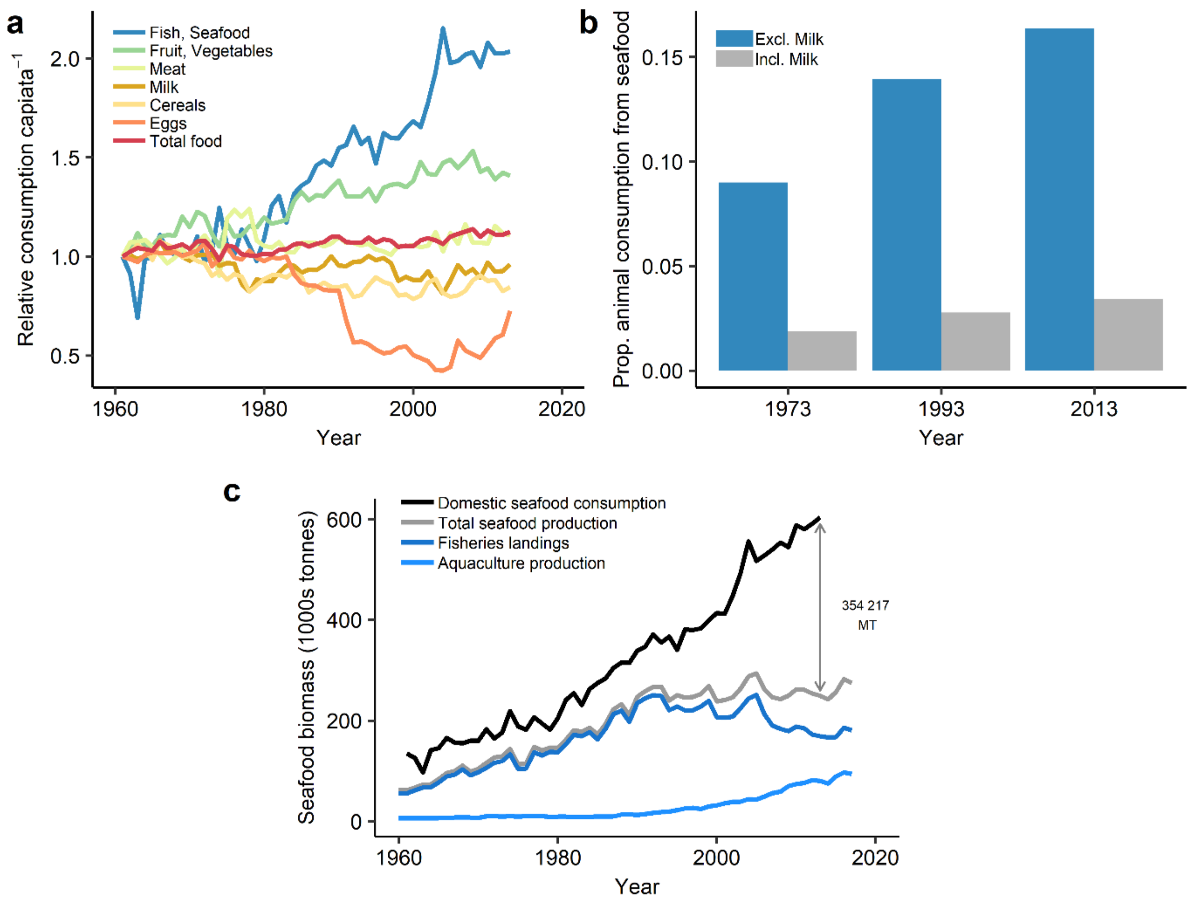


Figure 17 – Land-sea shifts in Australian food consumption. a) Relative consumption across key food commodities b) Seafood as a proportion of animal consumption through time, including and excluding milk c) Trends in Australian seafood consumption and production across fisheries and aquaculture sectors. Data from FAO (2019a).

While food demand continues to shift towards aquatic systems, the capacity to meet this demand through domestic seafood production is falling behind. Total Australian seafood consumption reached approximately 600 thousand tonnes in 2013 (although we acknowledge this is apparent consumption and includes waste and non-food usage), while current production capacity sits at approximately half of that (Figure 17c). Capture fisheries landings still dominate Australian production, fluctuating between 160-180 thousand tonnes from 2012-2017 while aquaculture production remained below 100 thousand tonnes in 2017

(Figure 17c). Aquaculture production continues to grow while landings from wild capture have plateaued and declined in the last 20 years. Consequently, the gap between production and consumption is widening (Figure 17c). Seafood is one of the most traded food commodities globally (Watson et al. 2017) and fish consumed in any given country is often from external sources irrespective of whether domestic production meets consumption or not. This is largely a reflection of the exchange in high and low-quality seafood products among developed and developing nations as an income generation strategy (Watson et al. 2017). However, the widening consumption-production gap in Australia means that environmental and social impacts of seafood consumption are increasingly unaccounted for in the place demands are coming from.

5.3.2. Imported seafood and exported sustainability challenges

Currently increasing Australian seafood demands are being met through imports and this is expected to increase under the National Food Plan (DAFF 2013). A large proportion (>60%) of current Australian seafood imports come from rapidly developing Asian trade partners. Seafood products imported from these nations benefits both the exporting countries in terms of domestic revenue but also increasing access to low-cost seafood for Australian consumers (Watson et al. 2017, Asche et al. 2015). Further, recent estimates suggest Australian seafood imports can have equivalent and sometimes lower carbon footprints than products produced domestically (Farmery et al. 2015). However, increasing dependence on these sources into the future has substantial implications across a broader and more embedded suite of sustainability metrics, challenging national responsibilities to responsible consumption targets.

Combined pressure of low environmental protection, high prevalence of overfishing, destructive fishing techniques and marine pollution mean that for 13 of the top 20 seafood trade partners (representing ~ 90% of all Australian imports), progress towards targets for protecting life below water (SDG 14) are lagging behind that of Australia (Figure 18). For many of Australia's key trade partners such as Vietnam, Indonesia, Thailand, or Malaysia, aquatic food production remains a significant threat to aquatic biodiversity, with relatively high numbers of threatened marine species when compared globally (Blanchard et al. 2017). Due to the opacity of global trade data, it is difficult to identify whether seafood imports are actually produced in the waters of trade partners via farming or fishing, or whether they are simply imported from elsewhere, packaged, processed and then re-exported (Gephart et al. 2019, Bellmann et al. 2016). Nonetheless, there are other concerns across seafood supply chains in many of Australia's trade partners that challenge the sustainability of imported seafood.

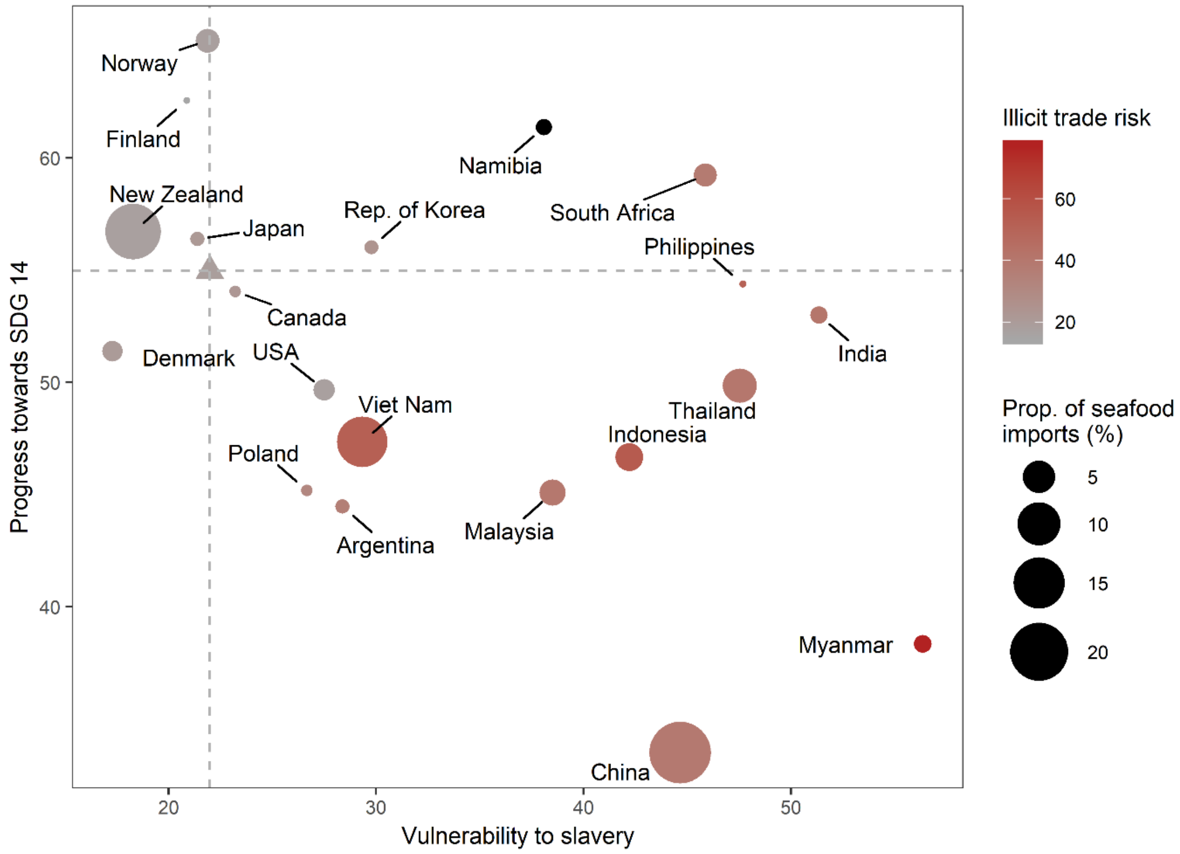


Figure 18 – Social and environmental sustainability dimensions of Australian seafood imports. Vulnerability to slavery in seafood supply chains increase further right on the horizontal axis, and progress towards SDG 14 improves further up the vertical axis. The size of the bubble indicates the proportion of imported Australian seafood from a given trade partner, and the shading indicates the risk of illicit trade from these countries. All sustainability indices are normalized scores between 0 -100 taken from the Global Slavery Index (Walk Free Foundation 2018), SDG Index and Dashboards Report 2018 (Sachs et al. 2018) and Economist Intelligence Unit (EIU 2018). Seafood trade data from COMTRADE database (United Nations 2019). The triangle at the intersection of the dashed lines represents Australia's position in terms of slavery vulnerability, SDG 14 progress, and illicit trade risk. Black fill for Namibia indicates no data on illicit trade.

Global decreases in fisheries yields (Rousseau et al. 2019) combined with perverse subsidies mean fishing fleets are travelling greater distances to maintain catch (Watson et al. 2015), increasing the need to reduce expenditure, and this may be done through non-compliance with safety standards or withholding pay from the crew. (Tickler, Meeuwig, Palomares, et al. 2018). With vessels now at sea for many months and crew unable to disembark, incidences of extreme labour abuse and slavery in fisheries have been uncovered recently (Tickler, Meeuwig, Bryant, et al. 2018). And in some of Australia's major seafood trade partners such as China, Myanmar, India, and Thailand, the vulnerability to slavery within seafood supply chains is particularly high (Figure 18). Embedded within the supply chains of many of these countries is also the potential for trading of illegally acquired seafood products (another symptom of decreasing fisheries yields and the race to fish) because of insufficient or ineffective laws, regulations and governance at combatting illicit trade (Tickler, Meeuwig, Bryant, et al. 2018, EIU 2018) (Figure 18). Thus, continuing to displace increasing demands for Australian seafood onto these systems may mean sustainability goals across aquatic food production sectors remain out of sight for these countries.

5.3.3. Addressing land-sea shifts through growth in domestic seafood production

It is important that trade-relationships, particularly with developing nations, are maintained to allow countries to develop economically, promote sustainable livelihoods and improve food security (Asche et al. 2015). However, Australia needs to take greater responsibility for the impacts of its seafood demands as they increase, given the already high per-capita consumption rates (26kg capita^{-1} yr^{-1} vs the global average of ~20.2kg in 2013; FAO 2018) and the sustainability concerns in the supply chains of traded seafood. Yet the capacity for meeting increasing Australian demands for fish through domestic wild capture is limited.

Decreases in national fisheries landings since the mid-2000s (Figure 19a) reflect fundamental restructuring under an ecological sustainable development framework to maximise economic efficiency of fishing operations, yield ecological co-benefits and safeguard fisheries against volatility in fuel prices, exports and competition from farmed fish commodities (Emery et al. 2017, Newton et al. 2007). These are particularly positive measures that adopt a precautionary approach to fisheries management and reflect the high ranking of Australia's federal fisheries governance at a global scale (Pitcher et al. 2009).

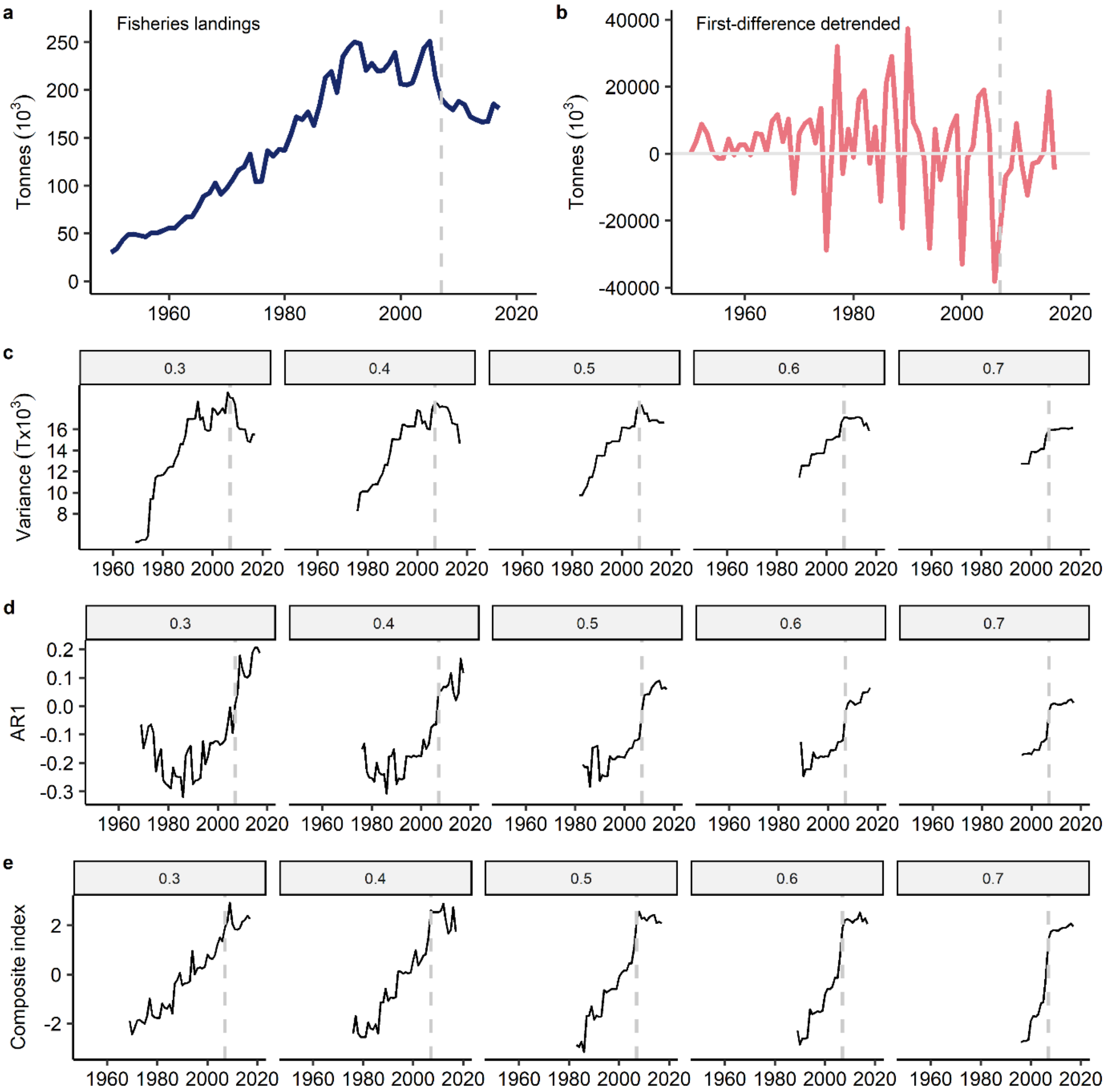


Figure 19– Early warning signals in Australian capture fisheries. a) Reported landings data for Australia. b) Detrended landings data using first differencing (see Appendix Figure 12 for autocorrelation checks) c) Variance in detrended residuals through time using different rolling window widths covering 0.3, 0.4, 0.5, 0.6, or 0.7 of the time series. d) Autocorrelation at the first lag (AR1) of detrended residuals through time using different rolling window widths covering 0.3, 0.4, 0.5, 0.6, or 0.7 of the time series. e) Composite indices of variance and autocorrelation across all rolling window widths.

Before industry restructuring, landings began to plateau in the 1990s (Figure 19a). As landings level off we detect statistically clear increases in the variance and autocorrelation (and their combined normalised signal) of detrended landings data until 2007 when variance started to stabilise (Figure 19,b-e). Such characteristics within time-series are temporal phenomena often used to provide early warning signals of an approach tipping point in social-ecological systems (Scheffer et al. 2012, Dakos et al. 2014). Such tipping points or critical transitions in ecological systems can arise as gradual changes in some underlying condition of a system causes a loss of resilience, where even small disturbances can shift the system into an alternative state (Dakos et al. 2012, Clements & Ozgul 2018, Folke et al. 2004, Scheffer et al. 2012, Dakos et al. 2014, Hughes et al. 2013). Non-linear changes to an ecosystem state are exemplified in a sudden collapse of a fish stock for example (Selkoe et al. 2015), and early warnings signals have been detected before the collapse of other populations as a result of extraction (Clements et al. 2017, Carpenter et al. 2011).

Non-linear responses in our landings data may be detected when populations return slower to equilibrium following a disturbance - a trend known as critical slowing down. As recovery slows, abundance becomes increasingly similar at consecutive time-steps and so autocorrelation at the first lag increases (Dakos et al. 2012). Variance is also expected to rise as slow return rates make the system drift widely about the equilibrium or flicker between alternative states (Dakos et al. 2012). Such changes to the abundance may then be reflected in the fisheries landings, until the system is unable to recover, whereby a non-linear response is observed as a transition to an alternative state. However, our analysis did not detect any residual non-linearities in the detrended landings data following Broock, Dechert and Scheinkman (BDS) testing (Brock et al. 1996; see Appendix Table 7), and so the decreases in landings since the mid-2000s are likely a consequence of multiple linear processes (such as management interventions) rather than from experiencing a ‘tipping point’. Nonetheless, with these statistical indicators detected in Australian fisheries landings leading up to restructuring in the 2000s, increasing fishing intensity beyond present exploitation levels to meet additional fish consumption into the future is unlikely to be a sustainable or significant solution, at least under the current management paradigm.

In contrast, Australian aquaculture production has enjoyed a rapid upward trajectory since the 1960s. Production has more than doubled since 2000 driven primarily by growth in the salmon industry (Figure 17c, Appendix Figure 13). However, expanding growth has been challenged in recent times by a loss of social acceptance in Tasmania where most production (>60% of total) occurs (Mosby 2018). Concerns surrounding high stocking densities, pollution, interactions with endangered species, and the adequacy of environmental regulations (in Macquarie harbor in particular), has led to a mediatized environmental conflict surrounding aquaculture in coastal waters (Cullen-Knox et al. 2019). Public perceptions of the aquaculture industry remain poor. Sentiment analysis of news headlines relating to aquaculture across Australian states and territories illustrates the dramatic spatial differences in perceptions (Figure 20a). The proportion of negative sentiment towards aquaculture by state also closely corresponds to the proportion of domestic production occurring in that state. Tasmania exhibits the most negative perceptions and is where the majority of domestic production occurs and is followed by South Australia the second most significant state for aquaculture production and so on (Figure 20b). While achieving a 'social licence to operate' is not a legal prerequisite for activity in any primary industry, social acceptance of emerging activities where new stakeholder conflicts can arise, can improve companies' likelihood of obtaining new leases and achieving growth. This is exemplified by the ensuing void in public trust in the aquaculture industry in Tasmania which remains a barrier to development (Vince & Haward 2019).

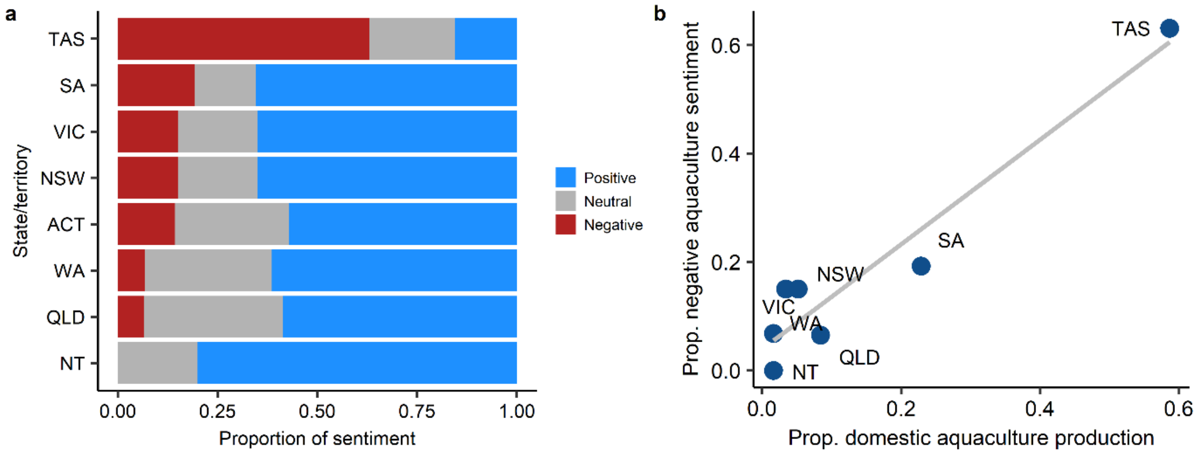


Figure 20 – Public perceptions of aquaculture across Australian states and territories. a) Sentiment analysis of news headlines relating to aquaculture from July 2017 to July 2018 b) Relationship between the proportional burden of domestic aquaculture carried by each state/territory and the proportion of aquaculture-news with negative sentiment.

Without aquaculture growth, however, sustainably addressing land-sea shifts in Australian consumption will become increasingly difficult unless significant shifts in trade patterns occur which will inevitably involve other socioeconomic trade-offs. Biophysical conditions are conducive to aquaculture growth in Australia - while the majority of global aquaculture is freshwater, most of Australia's production is marine (FAO 2019a), reducing reliance on increasingly scarce domestic freshwater resources that continue to challenge agriculture (although global water usage exist through feeds (Troell, Metian, et al. 2014)). There has also been tremendous innovation for sustainable aquaculture feeds in recent years, where the use of fishmeal and oil that drawn so much negative scrutiny in previous years (Naylor et al. 2000a, Naylor & Burke 2005), has reduced dramatically. These changes have occurred largely because of technical and nutritional innovation which has increased use of crops and animal by-products (such as bone and feather) in feeds but also the efficiency in which fish turn feed into biomass (Troell, Naylor, et al. 2014, Tacon & Metian 2008, Fry et al. 2016). Numerous novel feeds are also being tested and commercially implemented for the sparing of fishmeal and oil using algae, yeast, bacteria or insect-based feeds (Mahan et al. 2018, Shah et al. 2018, van Huis 2013). Fishmeal and oil-free salmon feeds are now in circulation from Skretting, one of the biggest feed suppliers to Australian aquaculture (Skretting 2019). Many of the key Australian aquaculture and feed producers are also actively engaging with the sustainability framework set out in the SDGs at multiple points along the supply chain (Skretting 2017, Fleming et al. 2017).

Aquatic sources of animal-protein fished and farmed in Australia can also have far lower environmental footprints across greenhouse gas, acidification, land-use, energy use, or eutrophication impacts than terrestrial livestock (Poore & Nemecek 2018, Hilborn et al. 2018). This may be important if land-sea consumption shifts strengthen because demands for terrestrial animal protein are further limited by increasing volatility in terrestrial production. Extreme weather in Australia poses continuing and cumulative threats to livestock production– prolonged drought followed by flood inundation in 2018-19 led to catastrophic cattle losses in Queensland (ABC News 2019, ABARES 2019). Concern over water and fodder shortages have led to significant declines in milk production since 2000 and subsequent structural changes to the dairy industry (Wales & Kolver 2017, ABARES 2019, Alston et al. 2017). While total meat production in Australia is still broadly accounting for Australian consumption (Appendix Figure 14), it is not clear whether this can continue as food production shocks from drought, flooding and tropical storms increase in frequency (Cottrell et al. 2019). Increased meteorological volatility has already caused dramatic increases in the variance of domestic crop production, particularly wheat and sugarcane (Hochman et al. (2017); Appendix Figure 15). These pressures on land could provide an important stimulus for increased growth in marine foods in Australia.

5.3.3. Opportunities for aquaculture to promote sustainable food system growth

The great potential for aquaculture growth sits partly in the diversity of species that can be farmed and tailored to social, economic and environmental conditions. Compared to terrestrial systems, greater diversity of aquatic species (and their associated production practices) provide key opportunities to minimize the environmental impacts of production (Troell, Naylor, et al. 2014). Policy on Australian aquaculture growth could support the development and diversification of species toward those most efficient in their environmental impact that also minimize trade-offs on other key objectives such as economic value and health benefits to consumers (Halpern et al. 2019). But at present domestic aquaculture is dominated by a few high-value species such as salmon, tuna, and shrimps (Bogard et al. 2019), which leaves the door open for cheaper seafood of questionable sustainability to enter the market.

While the species grown is often driven by market demand, nonvoluntary and voluntary certification schemes such as those from the Australian Marine Conservation Society (https://www.marineconservation.org.au/sustainable-seafood-choices/) or the Aquaculture Stewardship Council (ASC; https://www.asc-aqua.org/) respectively, are having a greater influence on consumer decisions in the Global North (Bush et al. 2013). As an example, the ASC provides standards to which producers must uphold environmental stewardship concerning preserving natural habitats and water resources, protecting wild populations of farmed species near aquaculture facilities, pollution around pens from nutrients, parasiticides, and infrastructure debris, alongside responsible feed sourcing and the welfare and health of the farmed species. There are also equally weighted social standards that require safe working conditions, fair pay, engagement with stakeholders and ensure farms do not negatively affect local communities (Aquaculture Stewardship Council 2015). Although a major criticism of current aquaculture certification schemes is a skew towards environmental impacts but lacking in other facets of sustainability, particularly those surrounding the social impacts of aquaculture (Osmundsen et al. 2020). These standards are constantly evolving through time, however, and certification can be revoked if producers are found to be uncompliant as monitoring is conducted on an ongoing basis. Compliant practices then have their products certified with a customer-facing logo allowing consumer choice to support best practice (Aquaculture Stewardship Council 2015). Such a process holds the potential for supporting the growth of a more diverse aquaculture industry in Australia.

A key challenge for increasing the sustainability of Australian aquaculture and using these certification schemes as a framework for diversifying production is creating the new markets for less known and lower-cost species that can substitute fish sources from imports of questionable sustainability (Bogard et al. 2019). Public education programs on environmentally appropriate species and their food preparation methods is one potential approach (Zhou et al. 2015, Riley & Buttriss 2011), although targeting seafood retailers may be more effective and may be efficiently achieved through Asian food culture in Australia where a greater of diversity of seafood is accepted (Bogard et al. 2019). Nonetheless, certification and public awareness programs must be conducted in parallel efforts in state legislation, *voluntary* better management practices (Bush et al. 2013) and even new behavioural tools that have been found to successfully ‘nudge’ people towards more environmentally friendly or healthy dietary choices (Rose 2018, Lehner et al. 2016, Reisch et al. 2017, Van Gestel et al. 2018).

One existing arena where exploiting species production practices and diversity can reduce negative environmental externalities while utilizing existing production systems is through Integrated Multitrophic Aquaculture (IMTA). IMTA is the co-culture of fed species such as finfish or shrimp, with extractive species such as algae, mussels, or sea cucumbers which feed from dissolved and particulate feed waste and faeces, to reduce nutrient pollution from the fed species while generating economically valuable coproducts (Buck et al. 2018, Troell et al. 2009). While ensuring economic viability and safety of all companion crops in IMTA remains a challenge (Buck et al. 2018), there appears good potential for IMTA in Australia, particularly surrounding salmon. For instance, particulate matter from salmon farms have shown good potential for utilization by mussels, and metal concentrations (a key concern for safety of companion crops) appeared within safe limits in kelp co-cultivated with salmon in Ireland (Ratcliff et al. 2016). Numerous extractive companion species are suitable for growth in Australia, particularly algae. Multiple native genera of red algae provide sources of agar, commercially sought after by food, pharma- and nutraceutical industries (Winberg et al. 2009). Green (*Ulva spp*) and brown algae or kelp (*Eklonia or Sargassum spp*) also provide sustainable feed sources for aquatic and terrestrial livestock or can be harvested for food directly (Winberg et al. 2009, Wiltshire et al. 2015, Angell et al. 2016). While IMTA remains in its infancy in Australia, there are promising signs of success from commercial-scale trials of kelp culturing alongside salmon farm leases in Southeast Tasmania (Tassal 2018), and this may help alleviate some of the growing concerns for nutrient pollution in coastal waters (Wiltshire et al. 2015).

Proactive movements towards more integrated production units in Australian aquaculture may help prevent future complications surrounding social acceptance. While public perceptions are largely negative in Tasmania, there appears a far more positive sentiment for aquaculture in general in all other states and territories, illustrating the opportunity that the aquaculture industry holds (Figure 20a). It is important to recognize that news headlines reflect proxies for public sentiment and that perceptions regarding aquaculture can differ among subsectors (Mazur & Curtis 2008). Yet these spatial differences in aquaculture perceptions can help shape policy on aquaculture that accounts for social and environmental concerns as the industry grows.

Maintaining its ‘social licence to operate’ should be a key priority for the aquaculture industry in the coming years. The innovation in feed, nutrition, and on-farm technology, coupled with increased accountability for supply chain impacts in many of the top producers and feed companies are driving huge improvements in local and global sustainability, but this alone may be insufficient. For example, Australia's largest salmon producer, Tassal, gained full accreditation from the Aquaculture Stewardship Council in 2015 in recognition of gold standards in codes of practice (ABC News 2015). Yet, the capacity for NGOs and the media to steer public opinions has been overwhelming, negatively affecting shareholders confidence in the company (Vince & Haward 2019). Given apparent positive sentiment across the rest of Australia, it is crucial that other elements of the aquaculture sector avoid these complications, which may only be resolved through developing mutual trust through time (Vince & Haward 2019).

Ultimately, expansion of aquaculture into coastal waters amidst other stakeholder uses is unlikely to be popular. Defensive resistance to changing resource use near existing industries and communities is unsurprising and a dynamic that has been experienced with other new industries such as the introduction of genetically modified organisms in EU farming or renewable energy production (Seifert 2008, Devine-Wright 2014). Opposition to aquaculture development in close proximity but indifference from further away is exemplified well in an Australian context - tuna and salmon remain the two single most consumed seafood taxa in Australia (Bogard et al. 2019) despite poor public perceptions of aquaculture industries in Tasmania and South Australia (Figure 20b) which are highly dominated by salmon and tuna farming respectively (Mosby 2018). Most of the consumed salmon is farmed in Tasmania (Bogard et al. 2019).

Part of the solution may rest on moving aquaculture growth away from the crowded coastal zone where conflicts over space for farming, fishing, transport, and recreation will continue to increase (Lester et al. 2018). Shifting operations into open waters is a favourable concept with huge capacity for industry expansion away from other user groups, high carrying and assimilation capacity, and reduced exposure to human sources of pollution (Holm et al. 2017, Troell et al. 2009). Experimental trials of moving Southern Bluefin Tuna ranches further offshore in South Australia have also demonstrated positive effects for reducing disease prevalence (Kirchhoff et al. 2011). With the third-largest marine jurisdiction of any nation, Australia holds some of the greatest global potential to expand offshore aquaculture (Australian Government 2015, Gentry et al. 2017).

Several barriers to offshore growth persist, however, and offshore aquaculture is still absent from Australia's National Aquaculture Strategy (Department of Agriculture and Water Resources 2017). Technological solutions for structural and mooring designs must first address the challenges posed by deep water, orbital swell, currents and marine mammal migration routes (Buck et al. 2018). Various novel designs from submerged mussel lines and finfish cages to closed containers in ship-designs are being tested worldwide but with as yet limited rollout (Buck et al. 2018, Goseberg et al. 2017). Combining these technologies with existing offshore energy structures may provide a key springboard with which to launch offshore aquaculture (Goseberg et al. 2017). This a key entry point for Australia which already plans to support growth in offshore energy sectors as part of its National Marine Science Plan (Australian Government 2015). However, the complex and disparate regulatory processes within and among jurisdictions that currently hinder aquaculture growth need to be streamlined (Department of Agriculture and Water Resources 2017). This will be particularly true if offshore aquaculture can be combined with IMTA approaches and regulatory mechanisms need to address production practices for multiple species and operations that could cross from state to commonwealth jurisdictions (Department of Agriculture and Water Resources 2017, Buck et al. 2018).

Across strategies, participatory planning involving public and private stakeholder groups will be vital. Many of the benefits of sustainable aquaculture including IMTA approaches are often unknown or misunderstood by the public which influences mainstream acceptance (Alexander et al. 2016). This is corroborated in our results by those states where greater production of more resource-intensive species such as shrimp occurs (such as Queensland or the Northern Territory) and fewer employment benefits from the aquaculture sector exist (Mosby 2018), few to no negative headlines about aquaculture were reported highlighting the potential for mismatches in perceptions and sustainability. Mitigating conflicts and the subsequent costs to industry and the community can be achieved if dialogue improves between industry, government and public actors, and perceptions are understood, acknowledged and responded to (Mazur & Curtis 2008). Movements towards land-based recirculating aquaculture systems (RAS) show increasing economic potential for growing salmonid species in other nations such as the US, Norway, and Denmark where there is limited capacity for production in coastal waters to expand due to strict regulations or ecological carrying capacity (Liu et al. 2016, Bjørndal & Tusvik 2019). RAS holds promise if production is to expand in areas where access to freshwater is less competitive than in major food bowls. While RAS recycles most of the water it uses it still requires access to surface or groundwater (Liu et al. 2016) and can conflict with other agricultural sectors with large scale expansion. Growth of RAS systems also poses sustainability challenges in terms of energy use which may be double that of open net-pen systems per unit of biomass produced (Liu et al. 2016). But if net-pen production is to grow, scientific, regulatory, and technological advancements to improve governance, economic and environmental efficiency of offshore operations will likely be a necessary step. The timely establishment of the $329 million Blue Economy Cooperative Research Centre in Tasmania – an international collaboration across 45 international partner organizations bringing together expertise across offshore technology, seafood production, environmental impact, renewable energy and governance programs (Blue Economy CRC 2019) – represents a crucial opportunity for achieving these goals.

5.4. Conclusions

The shift towards on average higher per capita consumption of seafood and widening gap between domestic seafood production and consumption are not unique to the Australian food system. We expect similar patterns in fisheries, trade, and social barriers to aquaculture development exist in other countries. In the same way, shifts in the opposite direction may occur, such as in Asia where meat is becoming a larger proportion of diets in urban areas. The implications of these changing consumption patterns will differ across specific countries and will be highly contextualised. However, in all cases, informing sustainable development pathways requires a much more integrated land-sea food systems approach to elucidate challenges and solutions that account for the interconnected global food system.

5.5. Methods

5.5.1. Data sources

Food consumption and production data

For consumption and production data across crop, meat, fish and seafood commodities, we used data from the United Nations Food and Agricultural Organization as this provided the most comprehensive temporal coverage with the greatest internal consistency. For consumption, we used food supply data from the FAOSTAT food balance sheets (http://www.fao.org/faostat/en/#data/FBS) and calculations concerning total food supply included total cereals, fruits, pulses, vegetables, starchy roots, spices, aquatic plants, vegetable oils, offals, meat, fish and seafood, milk and eggs. For gross domestic product (GDP relative to 2010 $USD) and population data, we used the World Bank Open Data

1960-2018 dataset (https://data.worldbank.org/). We used crop and livestock data from the FAOSTAT production quantity 1961-2017 dataset (http://www.fao.org/faostat/en/#data). Crop data covered 87 individual commodities grown in Australia, and we illustrate the top 10 in Appendix Figure 13. Meat production included meat from cattle (cow and buffalo), pigs, chickens, turkey, duck, sheep, goat, and horse. Milk production represents whole cow milk. We used the FAO FishStatJ database of ‘Global Capture Production’ and ‘Global Aquaculture Production’ for fisheries and aquaculture respectively, covering freshwater, brackish, and marine fishing and farming areas (FAO 2019b). Fisheries landings data covered 110 species with an additional 70 classifications of ‘not elsewhere included’ (e.g. Pufferfishes ‘nei’; i.e. undetermined species within a given taxon (Metian et al. 2019)), with aquaculture producing 27 listed species and 10 nei. State-level aquaculture production data was taken from the ABARES historic aquaculture production dataset (Mosby 2018).

Environmental and social sustainability data

To understand the sustainability implications of increasing dependence on imported seafood in Australia, we synthesised data from four sources. We used trade data from the United Nations COMTRADE database (https://comtrade.un.org/) to estimate the biomass of imported seafood from all commodities. To understand the environmental implications of importing seafood produced by trade partners, we used data on relative progress towards Sustainable Development Goal 14 (Life Below Water) for each trade partner from the Sustainable Development Solutions Network (Sachs et al. 2018). Scores for progress toward SDG 14 are calculated as normalised composite metrics accounting for six elements: the mean percentage area that is under protection in marine sites of key biological importance; the percentage of fish stocks collapsed or overfished within exclusive economic zones (EEZs); the percentage of fish caught via trawling; risk of extinction in marine species; extent of marine pollution in national jurisdiction; and comparisons between current fish stock biomass and stock biomass that can deliver maximum sustainable yield (Sachs et al. 2018).

To assess the social dimensions of seafood import sustainability we assessed the risk of slavery and illicit trade embedded in supply chains of trade partners. We used national-level data from the Global Slavery Index (GSI) (Walk Free Foundation 2018) as a proxy for vulnerability to slavery in fisheries, consistent with recent research (Tickler, Meeuwig, Bryant, et al. 2018). While the GSI is not specific to fisheries, it is a cross-sectoral measure of slavery prevalence at a national level that implicitly applies the same vulnerabilities to fishing, farming or fish processing sectors as any other. The GSI is calculated by a complex model fitted on individual and country-level risk factors for slavery given factors of governance structure and protection of civil rights (Walk Free Foundation 2018). We used The Global Illicit Trade Environment Index (EIU 2018) for country-level data on the risk of illicit trade. This index is constructed from literature reviews and expert elicitation and accounts for four main national indicators; the extent of legal frameworks for targeting illicit trade, transparency in trade practices and regulations regarding illicit trade, the state of institutional and economic variables that influence illicit trade; and customs efficiency at targeting illegal operations while maintaining open trade (EIU 2018). The Global Illicit Trade Environment Index is not specific to any commodity and so provides a proxy of illicit trade risk across all traded items including seafood.

5.5.2. Early warning signal analysis

We conducted all data synthesis and analyses on R statistical software (R Core Development Team 2017). To illustrate trends in meat and fish consumption as a response to per-capita GDP, we fitted a Poisson log-linear model using quasi-likelihood estimation. Generalised additive models (GAMs) were fitted to production time-series throughout using the mgcv package, with generalized cross-validation used to estimate the number of spline knots and thus smoothing. For early warning signal analyses, we calculated variance (standard deviation) and the autocorrelation at the first lag using 50% of the time-series as a rolling window. To generate p-values for Kendal tau correlation coefficients, we used bootstrap sampling with replacement repeated 1000 times.

5.5.3. Aquaculture perceptions analysis

To investigate how current public perceptions of aquaculture relative to other food sectors may hinder or bolster the capacity of the sector to grow in Australia, we conducted sentiment analysis of Australian news headlines about agriculture, aquaculture, or fisheries published from July 2017 to July 2018. While we recognise that headlines do not necessarily reflect precise opinions or their drivers and are not as accurate as interviews, they do offer tone and context that can rapidly shape reader perceptions (Froehlich et al. 2017), particularly in an increasingly mediatized world with time-starved readers. We limit the time span to a 12 month before this analysis to maintain manageable sample sizes and to reflect current rather than historical opinions which are less likely to shape future growth.

We searched Google News for relevant headlines for each Australian state and territory using the terms “(aquaculture OR fish farming) AND <State> AND AUSTRALIA” or “(fisheries OR fishing) AND <State> AND AUSTRALIA” or “agriculture AND <State> AND AUSTRALIA”. Repeating each search across the different states and territories uncovers spatial patterns in perceptions across food sectors but because of regional specialisation in production, spatial trends also reflect perceptions surrounding specific commodities. Searches returned a total of 1479 relevant headlines (agriculture = 617, aquaculture = 308, fisheries = 554) across all states and territories.

Authors RSC and AF analysed headline sentiment following the methodology by (Froehlich, RR Gentry, et al. 2017). To eliminate individual bias, both authors independently scored headline sentiment positive (1), neutral (0) or negative (-1) depending on how the headline reflects or intends to inform public opinion. Where mismatches in scores occurred, both authors re-read the headline and reached a consensus on sentiment. Irrelevant headlines to the sector in question were omitted through consensus. We adopted this method rather than automated approaches as there were important messages hidden in context in many headlines. For example, a headline of “Climate change disrupts Australian farming” may be construed as negative but it doesn’t reveal much regarding public opinion of agriculture, so this would be scored as neutral. In contrast, a slightly modified title of “Climate change disrupts Australian farming, families suffering” is very similar (both disrupts and suffering have negative connotations) but it reflects a sympathetic sentiment toward the plight of the industry via the families involved, and thus would be scored positive. Rates of disagreement in sentiment lexicons between authors were low (9% total – 7% of agriculture, 10% fisheries, 11% aquaculture) with opposite polarity (i.e. -1 and 1) assigned only twice (0.14% prevalence).

Chapter 6

6. General discussion

Terrestrial and aquatic food systems are integral to human nutrition and well-being but they are also some of the leading drivers of ecosystem degradation and biodiversity loss on our planet (Springmann et al. 2018, Campbell et al. 2017, Biggs et al. 2015, Willett et al. 2019), paradoxically undermining their own function. Meeting food demands for a human population growing in number and affluence, while alleviating poverty and hunger and maintaining a safe operating space for humanity are some of the largest, most important, and complex challenges we face as a species.

Strategies to improve sustainability of food production on land and sea are complicated by the links among terrestrial and aquatic sectors. Development and changes to resource use and availability in one sector can have implications elsewhere, as evidenced by surges in bushmeat hunting following fisheries declines in West Africa or the collapse of agricultural production in the USSR (Brashares et al. 2004, Bragina et al. 2015). Vulnerabilities to such interactions across land and sea are often exacerbated by the siloed operations of different governing bodies charged with the management of terrestrial or aquatic resources who may fail to anticipate sustainability threats from outside of their jurisdictions (Pittman & Armitage 2016, Álvarez-Romero et al. 2015). The range and consequences of links among food systems on land and sea are poorly understood, however, and still woefully underrepresented in food security research and policy. Fuller, integrative approaches to food system development are required as links among sectors become more pervasive under globalization and regional differences in the importance of terrestrial and aquatic foods must be accounted for (Halpern et al. 2019, Troell, Naylor, et al. 2014). Greater efforts in this field can inform a perspective of how links among systems can help drive synergistic benefits across them.

Using a mix of quantitative and qualitative approaches, this thesis contributes to knowledge in this arena by;

- Performing a comprehensive and systematic review of interactions among food systems on land and sea and their implication for biodiversity and food programs and policies;
- Quantifying the nutritional and economic potential of, and trade-offs from, sea-land switches in aquaculture feed sourcing as the price of fishmeal and oil increases
- Detecting sudden losses (or 'shocks') to national food production at a global scale and highlighting how these shocks can connect land and sea via linked challenges or the displacement of human resource use;
- Illustrating how land-sea shifts in food consumption patterns present new challenges and elucidate pathways toward food system sustainability.

6.1. Overview of key findings

Food production systems on land and sea are linked through a multitude of pathways. In Chapter 2, I show that most land-sea connections can be grouped into four main categories – ecosystem connectivity, feed interdependencies, livelihood interactions, and climate feedbacks. Ecosystem connectivity occurs because of disruption to the natural flow of subsidies (energy, material or organisms) among food production systems. Upstream water extraction disrupting downstream harvesting of fish, and agricultural run-off affecting coastal productivity, fisheries and aquaculture are typical examples. I do not address ecosystem connectivity or climate feedback explicitly in other parts of the thesis but largely focus on intersectoral demands for feed and land-sea interactions arising through shifting, or linked challenges to, human resource use.

With the plateau of global forage fish landings, the price of fishmeal and oil ingredients historically used in feeds has increased and the landscape of feed interdependencies among terrestrial and aquatic systems has had to shift to adjust. To find cheaper and more sustainable alternatives, aquaculture has turned to the use of more plant-based feeds and wider use of novel ingredients such as bacteria to supply dietary protein and lipids to farmed species. While these developments have been a central feature for improving aquaculture's perceived sustainability, there is a dearth of information surrounding the consequences of increased use of plant-based feeds with respect to the introduction of terrestrial material in to marine environments, the increased strain on agricultural crop systems, or the influence on the nutritional benefits of farmed species to consumers.

I address questions of feed efficiency and nutritional consequences of land-sea shifts in aquaculture diets in Chapter 3 through synthesizing and modelling 10 years of experimental data of forage fish replacement. Fishmeal and oil sparing using soy, insect, yeast, bacteria or algae ingredients tend to increase feed conversion ratios (making feeds less efficient and increasing overheads for producers) and decrease omega-3: omega-6 fatty acid ratios (reducing consumer health benefits) of farmed species, respectively. These trade-offs are more pronounced in feeds that use terrestrial ingredients such as soy or insects than with other aquatic ingredients such as algae. However, I show that there are thresholds of forage fish replacement where feed conversion and omega-3: omega-6 ratios under novel and plant-based feeds remain equivalent to fish-based reference diets. Applying these thresholds to species diets and simulating future projections of aquaculture's forage fish demand, I illustrated that even partial forage fish replacement can create huge savings in forage fish biomass, easing pressure on wild fish stocks. Crucially, I show that these savings can bring projected forage fish demand from aquaculture below the supply historically available from capture fisheries – an ecological limit that may otherwise be surpassed without intervention. Thus, it is likely that dietary shifts towards novel and plant-based ingredients in feeds will continue in aquaculture, however greater scrutiny of environmental or social trade-offs of their use is warranted. Closer examination of the role of increasing the proportion of fish supply coming from aquaculture has for the health of consumers who rely on fish as a key source of micronutrients is also needed (Belton et al. 2014).

Livelihood interactions also connect terrestrial and aquatic food systems through the partitioning of human resource use. Competition for space or resources can drive counter-productive outcomes for food production and security as growth in one sector undermines another. The rapid expansion of coastal aquaculture in Southeast Asia for the last 20 years and the ensuing problems of intrusion into agricultural land, soil salinization, destruction of nursery habitat important for fisheries, or recent conflicts between agricultural irrigation and fisheries in managed rivers in Australia provide key examples (Ahmed & Glaser 2016, Paul & Roskaft 2013, Paul & Vogl 2011, Harding et al. 2017, Richards & Friess 2015). More commonly food systems on land and sea can feed symbiotically into human livelihoods and food security. Livelihood diversification and alternative livelihood strategies are common around the world and frequently depend on both aquatic and terrestrial systems for food security (Fisher et al. 2017). Complimentary fish and farming strategies partitioned across households or through different seasons are common practices where food production is a primary livelihood activity and productivity in one sector can buffer families, communities, and economies from seasonal or unanticipated shortfalls in another (Cinner et al. 2012, Fisher et al. 2017, Sarch 1996). Income and commodities accrued through one livelihood activity are invested back into another, linking aquatic and terrestrial food systems through their own productivity.

While such livelihood links are globally important for food security, dependence across multiple sectors also highlights vulnerabilities. In Chapter 4, I show that food production shocks have increased globally since 1960 across crop, livestock, fisheries, and aquaculture sectors largely driven by extreme weather and geopolitical events (such as conflict and state dissolution). I found that for nearly 1 in 5 of national production time-series where a shock was detected, there were co-occurring shocks in other sectors across land and sea. For instance, in Dominica, shocks to agricultural production from hurricane damage were immediately proceeded by a surge in fisheries landings as a result of farmers turning to fishing activities for livelihoods. Such unanticipated displacement creates challenges for wider sustainability as shifts in human resource use may hinder management strategies in the receiving system. Indeed, only three years after the surge in fisheries landings in Dominica, I detected a shock to fish production thought to be linked to nearshore overfishing (Ramdeen et al. 2014). More commonly, however, shocks co-occurred in synchrony with production decreases common to both terrestrial and aquatic production. Linked challenges from food production shocks like this pose substantial threats to livelihoods and food security where shortfalls in multiple sectors can compromise diversification strategies and force people to derive food and income from unregulated systems.

The strong influence of extreme weather (particularly drought) and climate drivers to food production shocks detected in Chapter 4 reiterates the role of climate feedbacks among food systems. As major contributors to greenhouse gas emissions, food systems are also highly sensitive to climate change and these interactions are comprehensively reviewed in Chapter 2. Importantly, this work extends previous analyses that highlight the linked challenges to terrestrial and aquatic food systems faced under climate change, that while simultaneous gradual changes to food system productivity may occur across land and sea,(Blanchard et al. 2017) these shorter time-scale events can also pose significant barriers to provision of sufficient, safe, accessible and stable food in both realms.

Shifts in human resource use between land and sea can also occur as a result of consumption change and I explored the consequences of such shifts in Chapter 5. In Australia, per-capita increases in fish and seafood are rapidly outpacing changes in meat or vegetable consumption and thus an increasing proportion of Australian diets is being sourced from aquatic environments. However, Australian seafood production covers only about one-third of domestic consumption and ultimately this gap has consequences for the sustainability of food supplies. Domestic capture fisheries will be unable to fill this demand as landings have declined in recent years partly because of widespread economic restructuring but also climate change-induced environmental shifts, which are a growing concern for fisheries. Lack of stability is already evident with rising variance and autocorrelation present in landings data – two leading indicators of an approaching tipping point. Aquaculture has grown rapidly in recent years but now faces considerable barriers to growth due to problems with public trust. Consequently, the growing gap between production and consumption is being met through imports where there is considerable uncertainty regarding the sustainability of how the food is produced in terms of environmental efficiency but also social justice or the continuity of supply. Displacing the impacts of food demand onto other countries from a nation like Australia where per-capita consumption is one of the highest in the world, undermines progress towards sustainability targets such Sustainable Development Goal 12 for responsible production and consumption. Thus, appropriately accounting for the changing nature and pressures of human diets across land and sea are important considerations when aiming to improve food system sustainability.

6.2. Implications for food security, sustainability, and future work

The spectrum of links and interactions among food production systems on land and sea can create synergies, linked challenges or trade-offs for food security and sustainability. Without accounting for these multi-sector connections and threats in food security research and policy, we create critical blind spots in our attempts to sustainably increase food production and improve food security. For example, while alternative and diverse livelihoods across farming and fishing activities are often cited as important adaptation strategies in the face of extreme events (van Ginkel et al. 2013, Allison & Ellis 2001), I show in this thesis that food production shocks can reach across land and sea, compromising options for adaptation and reducing livelihood resilience. Furthermore, while I only detected displacements across the land-sea divide in response to shocks in one instance at a national level, these patterns may be more prevalent at smaller scales or when concerned with changes to individual commodities. Unregulated displacement of human resource use at local scales may be far harder to track and create complex challenges for responsible management of aquatic and terrestrial resources. Understanding how prevalent these switches are at local scales across different countries should, therefore, be a focus of future research, either by using local and national level statistics or through household surveys that more accurately address human responses to changing resource availability (e.g. Fluet-Chouinard et al. 2018). This knowledge in combination with an awareness of social-ecological challenges food systems face at these smaller scales can help build a holistic and targeted picture of how to approach sustainable development for a given location. Such work is particularly pressing as food production shocks appear to be increasing at a global scale without a clear reason, other than greater diversity of proximate drivers (Figure 13). The over-arching influence of climate change as an ultimate rather than proximate cause is still unclear but temporal trends in food production shocks of all types appear to exhibit close association with climatological and metrological variability (Figure 21).

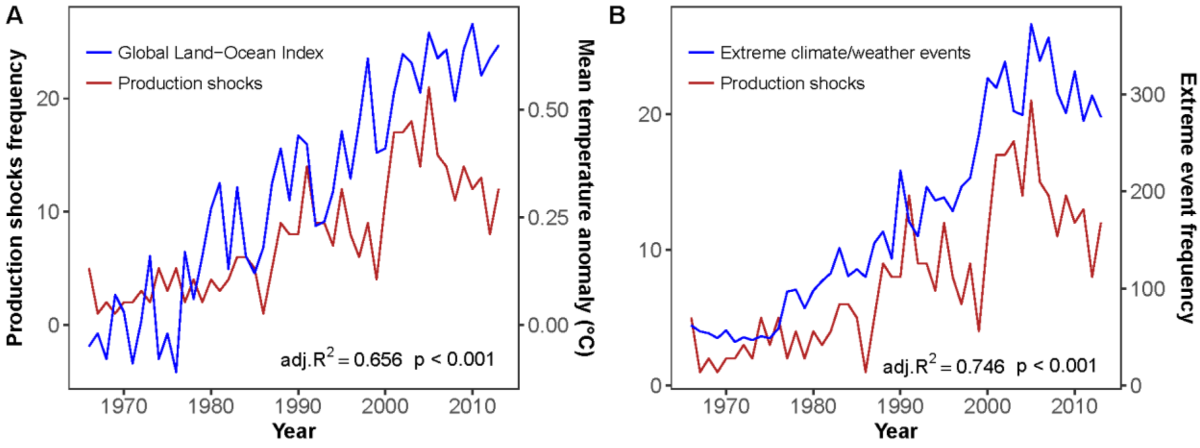


Figure 21 – Food production shocks association with climate indices. Correlation between total global food production shock frequency (across agriculture, fisheries and aquaculture from all shock drivers) and A) global mean combined land-sea temperature anomaly in degrees Celsius from NASA (GISTEMP 2019, Lenssen et al. 2019) or B) total global frequency of extreme climatological and meteorological events (storms, floods, droughts, and extreme temperatures) from the EMDAT international disasters database (EM-DAT 2018).

Further work is also required to understand land-sea trade-offs within the shifting landscape of aquaculture feeds. I show in Chapter 3 that while novel and plant-based aquaculture feeds can produce less efficient feed efficiencies and lower nutritional benefits in farmed aquatic species compared to using fishmeal and oil, even partial replacement that preserves these qualities holds potential for improved management of render fisheries that harvest forage fish stocks. Nonetheless, the benefits of using novel ingredients need to go beyond the capacity to reduce forage fish dependence and include a closer examination of other environmental and social metrics for sustainability. For example, the environmental benefits of using yeast or bacteria ingredients for forage fish replacement in salmon feeds may be dampened by greater inclusion of soy and wheat ingredients which dominate land, freshwater and eutrophication impacts (Couture et al. 2019, Gephart et al. 2014, Gephart et al. 2017).

Shifts towards greater crop inclusion in aquaculture feed, therefore, raises several sustainability questions across scales. Rapidly increasing demand for crops in feeds through aquaculture growth unavoidably drives increased global pressure on agricultural systems which are simultaneously charged with meeting increasing human food and terrestrial livestock feed demands. There are inescapable biophysical limits to how much food can be produced using current agricultural practices, soils, and land use. Already the efficiency in which we are producing feed crops is on the decline globally as yields per unit of fertilizer have consistently decreased since 2000 (Figure 22). Increased demand for feed crops can, therefore, lead to deleterious effects from intensification such as continued soil erosion and fertilizer-based nutrient pollution in aquatic systems or the expansion of agricultural land at the expense of natural ecosystems (Fry et al. 2016, Pahlow et al. 2015, Willett et al. 2019). There is also a paucity of information regarding the influence of introducing novel and plant-based feed ingredients into marine environments at local scales. The stoichiometry of plant and other terrestrial ingredients passed through fish waste do not necessarily correspond to stoichiometric relationships in marine environments. How these changes can influence bacterial and planktonic assemblages and accumulate through the food web in marine environments or influence nutrient cycling and waste production around fish farms has received very little attention, if any.

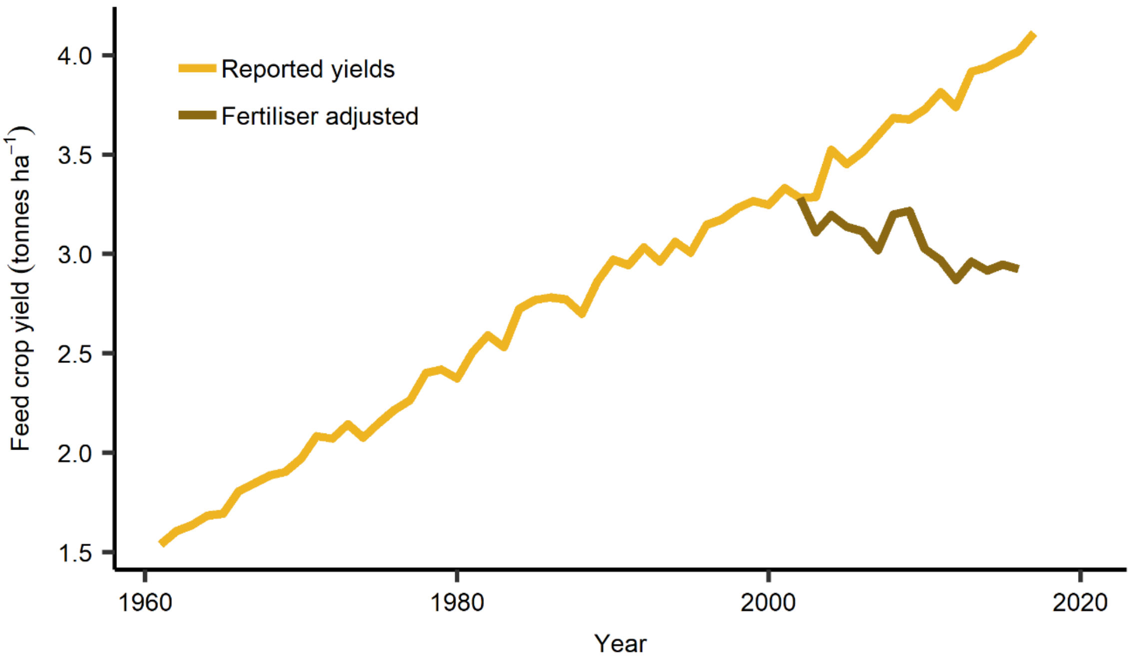


Figure 22 – Temporal trends in major feed crop yields. Reported global yields of major feed crops (wheat, maize, rapeseed, soy, rice, sorghum, peas and lupins, cassava, groundnuts, cottonseed, mustard seed, and sunflower seed; see Troell et al. (2014)) and adjusted by the global relative change in fertilizer consumption (dark line). Yields calculated as sum of production divided by production area for total feed crops. Adapted from work in review by Blanchard et al (see Appendix E). Data taken from FASOSTAT (FAO 2019a).

Understanding whether these trade-offs yield greater or lower sustainability for the food we eat will ultimately depend on the context of how and where feed products are produced or sourced from and the degree of scrutiny possible on supply chain operations. For example, soybean meal or oil sourced from Brazil carries the heavy environmental burden of modern deforestation (Heron et al. 2018), however, this must be balanced and standardised against the embedded impacts from production and trade practices elsewhere that can influence multiple dimensions of sustainability (Goucher et al. 2017, Farmery et al. 2015). Some feed ingredients may have lower environmental footprints in terms of greenhouse gas emissions or eutrophication potential, but others may carry a greater risk of human slavery or illicit trade in the supply chain for example (Tickler, Meeuwig, Bryant, et al. 2018, EIU 2018). Greater transparency in feed sourcing and formulation is, therefore, necessary at an industry level to address these trade-offs and force greater sustainability in business decisions. Once this information is available, both industry (augmented by initiatives such as the Aquaculture Stewardship Council, see Chapter 5) and academia can facilitate best practices in feed sourcing by accounting for the various social-ecological sustainability trade-offs through data synthesis and quantitative and qualitative modelling approaches. This work is the current focus of a collaboration I am fortunate to be part of, led by researchers from University of Tasmania in Australia and the University of Sheffield in the United Kingdom (see Appendix E for related works in review).

Much of the research in this thesis addresses how we are to meet the challenge of feeding a growing and increasingly affluent human population under the assumption that supply will aim to meet demand, driven largely by economic opportunity. Yet there is a deeper philosophical question of whether consumption trends should be driven by economics or whether we should aim to direct human consumption towards the most environmentally and socially sound food choices. Under current dietary trends, greenhouse gas emissions, nutrient pollution, land and freshwater use from global food production are all expected to increase by between 50 and 92% by 2050 and advance us towards planetary boundaries for changing land use, freshwater use, and ocean acidification (Springmann et al. 2018, Willett et al. 2019). Such a transgression would represent a significant threat to ecosystem function and food security at a global scale. A recent commission highlights the socio-environmental benefits of encouraging healthy human diets for reducing mortality through non-communicable diseases and reducing negative externalities of food production (Willett et al. 2019). Compared to typical dietary patterns across different regions of the world, optimum dietary patterns for human and environmental benefits would involve substantial per-capita increases in vegetables, fruit, whole grains, and nuts in most regions, with considerable reductions in red meat, eggs, and starchy vegetable consumption (Willett et al. 2019). Such changes should be feasible across various regions given that traditional diets in many Central American, Asian, European, and African nations have typically low meat inclusion and prominently plant-based (Willett et al. 2019).

As I highlight in Chapter 5, directing consumption towards environmentally and socially more responsible foods will be important if sustainability targets are to be met. Shifts towards greater proportions of aquatic products such as fish and molluscs in diets could provide huge potential for reducing the environmental impacts of consumption, but these shifts must be in place of, rather than in addition to, more-resource intensive products such as red meat in diets. By the same merit, if dietary trends are shifting towards greater proportions of meat as is clear in some Asian countries (Nam et al. 2010), aiming to promote more sustainable forms such as poultry over red meat will be important strategies for curbing greenhouse gas emissions, and reducing land and freshwater use, and improving human health (Willett et al. 2019).

But considering the huge variation around the environmental and social impacts of different food products (Willett et al. 2019, Springmann et al. 2018, Tilman & Clark 2014, Poore & Nemecek 2018), which ones are promoted should be carefully considered. In seafood, market demand is responsible for the expansive growth of fed species such as salmonids and shrimps, while unfed aquatic molluscs and small pelagic fish are far better at optimising nutritional benefits while reducing environmental impacts of production (Hallstrom et al. 2019, Farmery et al. 2018). Such considerations need to be accounted for when designing policy for responsible consumption. Further, with the projected required increases in fish supply set to come from aquaculture (FAO 2018), continued declines in water quality and environmental health surround farming sites in major producing nations (Luo et al. 2018, Henriksson et al. 2017) cannot be considered a sustainable solution.

The influence increasing the proportion of fish (or any other food type) in diets can also drive trade-offs within countries between domestic food security and local livelihood perspectives. Despite the growth in marine farming and the potential for offshore production, inland aquaculture in Asia is likely to remain the main source of farmed fish production into the future (Edwards 2015). While land and freshwater are limited resources on land, pond aquaculture has a high capacity to expand through rice/fish or rice/prawn cultivation or the conversion of marginal lands with poor soils into fish ponds (Edwards 2015). Such changes are likely to drive substantial economic benefits for poorer rice producers who own poor-quality land for growing crops but may challenge the overall necessity grow rice from a food security perspective (Edwards 2015). Although not a significant element of this thesis, considerations of shifting trends in global food production, distribution, and consumption and their influence on equity, particularly for small-scale poorer communities who are involved with food production is a fundamental step towards ensuring more widespread food security and resilience in the food system (Agarwal 2018, Godfray, Crute, et al. 2010, Godfray, Beddington, et al. 2010, Schipanski et al. 2016)

Despite a huge number of research articles and reviews have aimed to synthesize which foods are the most sustainable *to produce* (e.g. recent articles by Poore & Nemecek 2018, Godfray et al. 2018, Hilborn et al. 2018), much less information is available on how we translate this knowledge into more sustainable *consumption* (Rose 2018, Bianchi et al. 2018). Greater research focus on rational substitutability across terrestrial and marine products and behavioural nudges that address unconscious cognitive processes for decision making at the consumer level will be increasingly important in the future to most efficiently partition the environmental impacts of our food across land and sea.

Moreover, despite the continued research effort, our knowledge of which foods are more sustainable is based on remarkably incomplete data. Key papers focused on the environmental footprints of food production in recent years focus on only a few key food groups dominated by staple agricultural products, and are heavily skewed towards greenhouse gas emissions as a stressor (Halpern et al. 2019). This gap leaves large portions of our food system under-assessed, particularly for the high diversity of aquatic commodities. These under-assessed foods make up more than half of all animal production in 76 countries and over a quarter of total food production in 40 countries (Halpern et al. 2019). With data lacking on such large portions of their food systems, producing informed plans for moving toward sustainable development and food security is impossible for many nations (Halpern et al. 2019).

Funding and institutional priorities should be directed more towards integrated approaches to food system research across traditional land-sea boundaries to address some of these gaps. But greater financial support for reporting agencies that can track, estimate, and synthesise estimates of production that is currently hidden from national reporting statistics is also required (Halpern et al. 2019). Such funding boosts are also essential if we are to address fundamental gaps in the best available data that is painstakingly collected and analysed by organisations such as the FAO. Despite the huge coordinating effort that FAO conducts, substantial gaps exist in production data in particular, such as information on backyard farming or small-scale fisheries which are incredibly hard to reliably estimate (Ye et al. 2017). Although different datasets exist for fisheries (e.g. reconstructions by Watson 2017 or Pauly & Zeller 2016), all are based off FAO data and carry significant uncertainty surrounding their estimates of illegal or small-scale landings (Ye et al. 2017). Thus, better funding for FAO and similar organisations to better fill these gaps is a direct route to reducing this uncertainty. Further, this helps reduce the risk of compound errors that are inherent with most food system research relying on this singular data source with the capacity to overlook some of the most important systems from a food security perspective. In addition, a push for greater prevalence of ‘open data’ (i.e. data that is freely and publicly available following scientific enquiry and publication) is greatly needed, so that hard-earned funding for food system and sustainable development science is not spent on replicating existing work.

Recognition of the importance of food system linkages is growing along with an understanding of their capacity to drive some of the undesirable outcomes I discuss in this thesis. Dedicated food system working groups such as those at the National Center for Ecological Analysis and Synthesis, University of California Santa Barbara (www.nceas.ucsb.edu/projects/12776) and the Inter-Sectoral Impact Model Intercomparison Project (www.isimip.org) aim to provide clear and quantitative assessments of cross-sectoral links and the challenges they pose under global change. This will complement the efforts of other working groups aiming to standardise the environmental impacts of a comprehensive range of food types such as the HESTIA platform at the Oxford Martin Program on Food Sustainability Analytics (https://hestia.earth/). Such approaches are also pivotal if we are to if we want to exploit or create links for our advantage such as the co-benefits realized from feeding farmed algae to ruminants to reduce methane emissions (Brooke et al. 2018) or to use shellfish farming as an approach to sequestering nutrients from agricultural run-off (Froehlich et al. 2017). Realising symbioses across sectors within our food system maybe a critical tool for increasing food production while reducing negative environmental impacts into the future.

6.3. Conclusions

To meet food demands from a growing, more affluent population, while keeping the Earth system within safe planetary limits, dramatic changes to production practices and continued technological advancement will be necessary for food systems across land and sea. Agriculture, fisheries, and aquaculture are inextricably linked through connectivity within the Earth's biosphere and the redistribution of nutrients and resources from human activity. In an interconnected system, changes made to one aspect can result in changes to another. In an increasingly globalized world where connections are becoming more pervasive, understanding the nature, direction, and strength of interactions among terrestrial and aquatic food systems is critical to prevent unanticipated, negative outcomes for food security and sustainable development.

Quantifying the trade-offs that can occur from intersectoral connectivity can help guide decisions about their urgency or importance. For example, shifts away from fish-based aquaculture towards greater inclusion of novel and plant-based ingredients can yield important trade-offs among the economic viability of feeds and the health benefits of farmed fish and invertebrates for human consumption. But they can still be used to a point where these trade-offs are minimized while still providing an important tool for conservation of marine fish populations targeted for fishmeal and oil in the short-term. Likewise, sudden displacement of human resource-use from land to sea or vice versa in response to food shocks are considerable challenges for governance and sustainability targets. Yet if they are rare occurrences (as my analysis suggests) they are of less concern. What is more pressing are linked challenges across land and sea which can hinder the capacity for people to adapt to changing social-ecological conditions and require broader-scale social protection interventions to secure food security and sustainability.

Recognition of the need to address this greater level of complexity in the food system is growing in academic circles, but greater support is required from funding agencies and research institutions where barriers for cross-discipline research still exist despite the inherently social-ecological nature of the food system. Placing all foods from terrestrial and aquatic sectors on the same table for even-handed environmental and social impact assessments are fundamental steps towards sustainability planning, particularly in developing nations. Proactive measures to bridge the land-sea divide in food system research and policy are urgently required if we are to gain a complete perspective of our food system and more holistically address global ambitions for food security and wider sustainability.

References

ABARES 2019, *Agricultural Commodities: June quarter 2019, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, June. CC BY 4.0.*

ABC News 2015, *Tasmanian salmon producer Tassal achieves world first with WWF sustainability certification*, <https://www.abc.net.au/news/2014-11-15/tasmanian-salmon-producer-recognised-sustainablility-practices/5893764>.

ABC News 2019, 'Cattle, infrastructure losses following Queensland floods could near $2b, farm lobby says', , p. abc.net.au/news/rural/2019-04-16/cattle-deaths-tal, <https://www.abc.net.au/news/rural/2019-04-16/cattle-deaths-tal>.

Agarwal, B 2018, 'Gender equality , food security and the sustainable development goals', *Current Opinion in Environmental Sustainability*, vol. 34, pp. 26–32.

Ahmed, BN & Waibel, H 2019, 'The role of homestead fish ponds for household nutrition security in Bangladesh', *Food Security*, vol. 11, no. 4, pp. 835–854.

Ahmed, N & Glaser, M 2016, 'Coastal aquaculture, mangrove deforestation and blue carbon emissions: Is REDD+ a solution?', *Marine Policy*, vol. 66, pp. 58–66.

Ahmed, N, Ward, JD, & Saint, CP 2014, 'Can integrated aquaculture-agriculture (IAA) produce more crop per drop', *Food Security*, vol. 6, no. 6, pp. 767–779.

Alexander, KA et al. 2015, 'The implications of aquaculture policy and regulation for the development of integrated multi-trophic aquaculture in Europe', *Aquaculture*, vol. 443, pp. 16–23.

Alexander, KA et al. 2019, ‘Progress in integrating natural and social science in marine ecosystem-based management research’, *Marine and Freshwater Research*, vol. 70, no. 1, pp. 71–83.

Alexander, KA, Freeman, S, & Potts, T 2016, ‘Navigating uncertain waters: European public perceptions of integrated multi trophic aquaculture (IMTA)’, *Environmental Science and Policy*, vol. 61, pp. 230–237, <http://dx.doi.org/10.1016/j.envsci.2016.04.020>.

Alexandratos, N & Bruinsma, J 2012, *World agriculture towards 2030/2050*.

Alhazzaa, R, Nichols, PD, & Carter, CG 2018, ‘Sustainable alternatives to dietary fish oil in tropical fish aquaculture’, *Reviews in Aquaculture*.

Allison, E & Ellis, F 2001, ‘The livelihoods approach and management of small-scale fisheries’, *Marine Policy*, vol. 25, no. 5, pp. 377–388.

Allison, EH 2011, ‘Aquaculture, Fisheries, Poverty and Food Security’, *WorldFish Center Working Paper*, vol. 65.

Allison, EH & Horemans, B 2006, ‘Putting the principles of the Sustainable Livelihoods Approach into fisheries development policy and practice’, *Marine Policy*, vol. 30, no. 6, pp. 757–766.

Alston, M, Clarke, J, & Whittenbury, K 2017, ‘Gender relations, livelihood strategies, water policies and structural adjustment in the Australian dairy industry’, *Sociologia ruralis*, vol. 57, pp. 752–768.

Álvarez-Romero, JG et al. 2011, ‘Integrated Land-Sea Conservation Planning: The Missing Links’, *Annual Review of Ecology, Evolution, and Systematics*, vol. 42, no. 1, pp. 381–409.

Álvarez-Romero, JG et al. 2015, ‘Integrated cross-realm planning: A decision-makers’ perspective’, *Biological Conservation*, vol. 191, pp. 799–808.

Angell, AR et al. 2016, ‘Seaweed as a protein source for mono-gastric livestock’, *Trends in Food Science and Technology*, vol. 54, no. November, pp. 74–84.

Aquaculture Stewardship Council 2015, *The principles behind the ASC standards*, , p. https://www.asc-aqua.org/the-principles-behind-the, <https://www.asc-aqua.org/the-principles-behind-the-asc-standards/>.

Arechavala-Lopez, P et al. 2013, ‘Reared fish, farmed escapees and wild fish stocks - A triangle of pathogen transmission of concern to Mediterranean aquaculture management’, *Aquaculture Environment Interactions*, vol. 3, no. 2, pp. 153–161.

Arechavala-Lopez, P et al. 2015, ‘Aggregations of wild Atlantic Bluefin Tuna (Thunnus thynnus L.) at Mediterranean offshore fish farm sites: Environmental and management considerations’, *Fisheries Research*, vol. 164, pp. 178–184.

Arthur, R et al. 2013, ‘Fisheries and aquaculture and their potential roles in development: an assessment of the current evidence’, *MRAG, Institute of Development Studies*, , no. June.

Asche, F et al. 2015, ‘Fair Enough? Food Security and the International Trade of Seafood’, *World Development*, vol. 67.

Asche, F, Bjørndal, T, & Young, JA 2001, ‘Market interactions for aquaculture products’, *Aquaculture Economics & Management*, vol. 5, no. April, pp. 303–318.

Asher, K & Shattuck, A 2017, ‘Forests and Food Security: What’s Gender Got to Do with It?’, *Social sciences*, vol. 6, no. 1, p. 34.

Atapattu, SS & Kodituwakku, DC 2009, ‘Agriculture in South Asia and its implications on downstream health and sustainability: A review’, *Agricultural Water Management*, vol. 96, no. 3, pp. 361–373.

Australian Government 2015, *National Marine Science Plan 2015 – 2025 Driving the Development of Australia’s Blue Economy*.

Avadí, A & Fréon, P 2013, ‘Life cycle assessment of fisheries: A review for fisheries scientists and managers’, *Fisheries Research*, vol. 143, no. February, pp. 21–38.

Barange, M et al. 2014, ‘Impacts of climate change on marine ecosystem production in societies dependent on fisheries’, *Nature Climate Change*, vol. 4, no. 3, pp. 211–216.

Barrett, CB 2010, ‘Measuring food insecurity.’, *Science (New York, N.Y.)*, vol. 327, no. 5967, pp. 825–828.

Barrington, K, Chopin, T, & Robinson, S 2009, ‘Integrated multi-trophic aquaculture (IMTA) in marine temperate waters’, *Integrated mariculture: a global review. FAO Fisheries and Aquaculture Technical Paper*, vol. 529, pp. 7–46.

Bartley, DM, Rana, K, & Immink, AJ 2000, ‘The use of inter-specific hybrids in aquaculture and fisheries’, *Reviews in Fish Biology and Fisheries*, vol. 10, no. 3, pp. 325–337.

Basurko, OC, Gabiña, G, & Uriondo, Z 2013, ‘Energy performance of fi shing vessels and potential savings’, *Journal of Cleaner Production*, vol. 54, pp. 30–40.

Bayer, AM et al. 2014, ‘The 1997–1998 El Niño as an unforgettable phenomenon in northern Peru: a qualitative study’, *Disasters*, vol. 38, no. 2, p. 351.

Begum, MR et al. 2015, 'Small-scale Integrated Aquaculture: A Tool of Poverty Alleviation, Gender Equality Promotion and Improving Food Security At Household Level In Coastal Region of Bangladesh', *International Journal of Agricultural Research, Innovation and Technology*, vol. 5, no. 2, pp. 82–85.

Belhabib, D et al. 2018, 'Impacts of anthropogenic and natural " extreme events " on global fisheries', *Fish and Fisheries*, , no. August 2017, pp. 1–18.

Bell, J et al. 2016,'Effects of ocean warming on the contributions of fisheries and aquaculture to food security', in D Laffoley & J Baxter (eds.), *Explaining ocean warming: causes, scale, effects and consequences*, Full report, IUCN., Gland, Switzerland, pp.409–438.

Bellmann, C, Tipping, A, & Sumaila, UR 2016, 'Global trade in fish and fishery products: An overview', *Marine Policy*, vol. 69, pp. 181–188.

Belton, B, Van Asseldonk, IJM, & Thilsted, SH 2014, 'Faltering fisheries and ascendant aquaculture : Implications for food and nutrition security in Bangladesh', *Food policy*, vol. 44, pp. 77–87.

Beman, J, Arrigo, K, & Matson, P 2005, 'Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean.', *Nature*, vol. 434, no. 7030, pp. 211–214.

Béné, C, Barange, M, Subasinghe, R, Pinstrup-Andersen, P, Merino, G, Hemre, GI, et al. 2015, 'Feeding 9 billion by 2050 - Putting fish back on the menu', *Food Security*, vol. 7, no. 2, pp. 261–274.

Béné, C, Barange, M, Subasinghe, R, Pinstrup-Andersen, P, Merino, G, Hemre, G-I, et al. 2015, 'Feeding 9 billion by 2050– Putting fish back on the menu', *Food Security*, vol. 7, pp. 261–274.

Berk, M 2018, ‘sme: Smoothing-Splines Mixed-Effects Models. R package version 1.0.2.’, , p. https://CRAN.R-project.org/package=sme.

Berry, EM et al. 2015, ‘Food security and sustainability: can one exist without the other?’, *Public health nutrition*, , no. 5, pp. 1–10.

Beveridge, M et al. 2010,‘Barriers to aquaculture development as a pathway to poverty alleviation and food security’, in, *Advancing the Aquaculture Agenda: Workshop Proceedings. OECD Publishing*, Paris, pp.345–359.

Bhagwat, SA et al. 2008, ‘Agroforestry : a refuge for tropical biodiversity ?’, *Trends in Ecology & Evolution*, vol. 23, no. 5, pp. 261–267.

Bhat, MG & Bhatta, R 2004, ‘Considering aquacultural externality in coastal land allocation decisions in India’, *Environmental and Resource Economics*, vol. 29, no. 1, pp. 1–20.

Bianchi, F et al. 2018, ‘Restructuring physical micro-environments to reduce the demand for meat: a systematic review and qualitative comparative analysis’, *The Lancet Planetary Health*, vol. 2, no. 9, pp. e384–e397.

Biggs, EM et al. 2015, ‘Sustainable development and the water–energy–food nexus: A perspective on livelihoods’, *Environmental Science & Policy*, vol. 54, pp. 389–397.

Bjørndal, T & Tusvik, A 2019, ‘Economic analysis of land based farming of salmon’, *Aquaculture Economics & Management*, vol. 23, no. 4, pp. 449–475.

Blanchard, JL et al. 2017, ‘Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture’, *Nature Ecology & Evolution*, vol. 1, no. 9, p. 1240.

Blue Economy CRC 2019, *Blue Eocnomy Cooperative Research Centre*, , p. https://blueeconomycrc.com.au/.

Blythe, JL 2013, ‘Social-ecological analysis of integrated agriculture-aquaculture systems in Dedza, Malawi’, *Environment, Development and Sustainability*, vol. 15, no. 4, pp. 1143–1155.

Bogard, JR et al. 2019, ‘Linking Production and Consumption : The Role for Fish and Seafood in a Healthy and Sustainable Australian Diet’, *Nutrients*, vol. 111, no. 1766.

Boland, MJ et al. 2013, ‘The future supply of animal-derived protein for human consumption’, *Trends in Food Science and Technology*, vol. 29, no. 1, pp. 62–73.

Bommarco, R, Kleijn, D, & Potts, SG 2013, ‘Ecological intensification: Harnessing ecosystem services for food security’, *Trends in Ecology and Evolution*, vol. 28, no. 4, pp. 230–238.

Bonhommeau, S et al. 2013, ‘Eating up the world ’ s food web and the human trophic level’, , vol. 110, no. 51, pp. 20617–20620.

Bouwman, L et al. 2013, ‘Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period’, *Proceedings of the National Academy of Sciences*, vol. 110, no. 52, pp. 20882–20887.

Bragina, E V. et al. 2015, ‘Rapid declines of large mammal populations after the collapse of the Soviet Union’, *Conservation Biology*, vol. 29, no. 3, pp. 844–853.

Brashares, JS et al. 2004, ‘Bushmeat hunting, wildlife declines, and fish supply in West Africa.’, *Science*, vol. 306, no. 5699, pp. 1180–1183.

Bravo-monroy, L, Potts, SG, & Tzanopoulos, J 2016, ‘Drivers influencing farmer decisions for adopting organic or conventional coffee management practices’, *Food Policy*, vol. 58, pp. 49–61, <http://dx.doi.org/10.1016/j.foodpol.2015.11.003>.

Breitburg, D 2002, ‘Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries’, *Estuaries*, vol. 25, no. 4, pp. 767–781.

Brinker, A & Reiter, R 2011, ‘Fish meal replacement by plant protein substitution and guar gum addition in trout feed. Part II: Effects on faeces stability and rheology’, *Aquaculture*, vol. 49, no. 1, pp. 27–48.

Bromham, L, Dinnage, R, & Hua, X 2016, ‘Interdisciplinary research has consistently lower funding success’, *Nature*, vol. 534, no. 7609, p. 684.

Broock, WA et al. 1996, ‘A test for independence based on the correlation dimension’, *Econometric reviews*, vol. 15, no. 3, pp. 197–235.

Brooke, C et al. 2018, ‘Methane Reduction Potential of Two Pacific Coast Macroalgae During in-vitro Ruminant Fermentation.’, *bioRxiv*, p. 434480.

Bruce, A 2017, ‘Genome edited animals: Learning from GM crops?’, *Transgenic Research*, vol. 26, no. 3, pp. 385–398.

Brussaard, L et al. 2010, ‘Reconciling biodiversity conservation and food security: Scientific challenges for a new agriculture’, *Current Opinion in Environmental Sustainability*, vol. 2, no. 1–2, pp. 34–42.

Buck, B et al. 2017,‘Offshore and Multi-Use Aquaculture with Extractive Species: Seaweeds and Bivalves’, in B Buck & R Langan (eds.), *Aquaculture Perspective of Multi-Use Sites in* *the Open Ocean: The Untapped Potential for Marine Resources in the Anthropocene*, pp.23–70.

Buck, BH et al. 2018, 'State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA)', *Frontiers in Marine Science*, vol. 5, p. 165.

Buhaug, H et al. 2015, 'Climate variability , food production shocks , and violent conflict in Sub-Saharan Africa', *Environmental Research Letters*, vol. 10, no. 125015, p. 12.

Bunholi, IV et al. 2018, 'The fishing and illegal trade of the angelshark: DNA barcoding against misleading identifications', *Fisheries research*, vol. 206, pp. 193–197.

Bureau, J & Swinnen, J 2018, 'EU policies and global food security', *Global Food Security*, vol. 16, pp. 106–115.

Bush, SR et al. 2013, 'Certify Sustainable Aquaculture?', *Science*, vol. 341, no. September 2013, pp. 1067–1069.

Butler, JRA, Cunningham, PD, & Starr, K 2005, 'The prevalence of escaped farmed salmon, Salmo salar L., in the River Ewe, western Scotland, with notes on their ages, weights and spawning distribution', *Fisheries Management and Ecology*, vol. 12, no. 2, pp. 149–159.

Cafer, AM et al. 2015, 'Growing Healthy Families: Household Production, Food Security, and Well-Being in S outh W ollo, E thiopia', *Culture, Agriculture, Food and Environment*, vol. 37, no. 2, pp. 63–73.

Cai, W et al. 2014, 'Increasing frequency of extreme El Niño events due to greenhouse warming', *Nature Climate Change*, vol. 4, no. 2, pp. 111–116.

Calzadilla, A et al. 2013, ‘Climate change impacts on global agriculture’, *Climatic Change*, vol. 120, no. 1–2, pp. 357–374.

Campbell, BM et al. 2017, ‘Agriculture production as a major driver of the Earth system exceeding planetary boundaries’, , vol. 22, no. 4.

Cao, L et al. 2015, ‘China’s aquaculture and the world’s wild fisheries’, *Science*, vol. 347, no. 6218, pp. 133–135.

Carpenter, SR et al. 2011, ‘Early warnings of regime shifts: a whole- ecosystem experiment’, *Science*, vol. 332, no. May, pp. 1079–1082.

Castine, SA et al. 2017, ‘Homestead pond polyculture can improve access to nutritious small fish’, *Food Security*, vol. 9, no. 4, pp. 785–801.

Chakraborty, S & Newton, AC 2011, ‘Climate change, plant diseases and food security: An overview’, *Plant Pathology*, vol. 60, no. 1, pp. 2–14.

Cheung, WWL, Watson, R, & Pauly, D 2013, ‘Signature of ocean warming in global fisheries catch.’, *Nature*, vol. 497, no. 7449, pp. 365–368.

Chiu, A et al. 2013, ‘Feed and fishmeal use in the production of carp and tilapia in China’, *Aquaculture*, vol. 414–415, pp. 127–134.

Chopin, T et al. 2012, ‘Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture’, *Reviews in Aquaculture*, vol. 4, no. 4, pp. 209–220.

Cinner, JE et al. 2012, ‘Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries’, *Global Environmental Change*, vol. 22, no. 1, pp. 12–20.

Clavelle, T et al. 2019, ‘Interactions and management for the future of marine aquaculture and capture fisheries’, *Fish and Fisheries*, vol. 20, pp. 368–388.

Clements, CF et al. 2017, ‘Body size shifts and early warning signals precede the historic collapse of whale stocks’, *Nature ecology & evolution*, vol. 1, no. 7, p. 188.

Clements, CF & Ozgul, A 2018, ‘Indicators of transitions in biological systems’, *Ecology letters*, vol. 21, no. 6, pp. 905–919.

Cole, AJ et al. 2016, ‘Seaweed compost for agricultural crop production’, *Journal of Applied Phycology*, vol. 28, no. 1, pp. 629–642.

Collins, V 2016,‘The Nomadic Pastoralist, the fisherman and the pirate’, in J Donnermeyer (ed.), *The Routledge International Handbook of Rural Criminology*, Abingdon, Oxon, UK and New York, NY, USA, p.93.

Cordell, D, Drangert, JO, & White, S 2009, ‘The story of phosphorus: Global food security and food for thought’, *Global Environmental Change*, vol. 19, no. 2, pp. 292–305.

Costa-Pierce, B 2008, ‘An ecosystem approach to marine aquaculture: a global review’, *… Ecosystem Approach To Aquaculture*, , no. May, <http://ecologicalaquaculture.org/FAOaquaecos.pdf#page=89>.

Cottrell, RS et al. 2017, ‘Considering land-sea interactions and trade-offs for food and biodiversity’, *Global Change Biology*, , no. August, pp. 1–17, <http://doi.wiley.com/10.1111/gcb.13873>.

Cottrell, RS et al. 2019, ‘Food production shocks across land and sea’, *Nature Sustainability*, vol. 2, no. 2, pp. 130–137.

Couture, JL et al. 2019, ‘Environmental benefits of novel nonhuman food inputs to salmon feeds’, *Environmental science & technology*, vol. 53, no. 4, pp. 1967–1975.

Craig, JF et al. 2004, ‘The Bangladesh floodplain fisheries’, *Fisheries Research*, vol. 66, no. 2–3, pp. 271–286.

Cullen-Knox, C et al. 2019, ‘Publicised scrutiny and mediatised environmental conflict: The case of Tasmanian salmon aquaculture’, *Marine Policy*, vol. 100, pp. 307–315.

Cury, PM et al. 2005, ‘Viability theory for an ecosystem approach to fisheries’, *ICES journal of marine science*, vol. 62, no. 3, pp. 577–584.

DAFF 2013, *National Food Plan, Our Food Future. Department of Agriculture, Fisheries and Forestry, Canberra*.

Dakos, V et al. 2012, ‘Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data’, *PLoS ONE*, vol. 7, no. 7.

Dakos, V et al. 2014, ‘Resilience indicators: prospects and limitations for early warnings of regime shifts’, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 370, no. 1659, pp. 20130263–20130263.

Davis, KF et al. 2015, ‘Historical trade-offs of livestock’s environmental impacts’, *Environmental Research Letters*, vol. 10, no. 12, p. 125013.

Davis, KF et al. 2016, ‘Meeting future food demand with current agricultural resources’, *Global Environmental Change*, vol. 39, pp. 125–132, <http://dx.doi.org/10.1016/j.gloenvcha.2016.05.004>.

Davis, KF & D'Odorico, P 2015, 'Livestock intensification and the influence of dietary change: A calorie-based assessment of competition for crop production', *Science of the Total Environment*, vol. 538, no. September, pp. 817–823.

Day, W, Audsley, E, & Frost, AR 2008, 'An engineering approach to modelling , decision support and control for sustainable systems', *Philosophical Transactions of the Royal Society B*, vol. 363, pp. 527–541.

De'ath, G et al. 2012, 'The 27-year decline of coral cover on the Great Barrier Reef and its causes.', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 109, no. 44, pp. 17995–9.

Degrande, A & Arinloye, D-DA 2014, 'Gender in agroforestry: implications for action-research', *Nature & Faune*, p. 6.

Department of Agriculture and Water Resources 2017, *National Aquaculture Strategy*.

Devereaux, S 2016, 'Social protection for enhanced food security in sub-Saharan Africa', *Food policy*, vol. 60, pp. 56–72.

Devine-Wright, P 2014, *Renewable Energy and the Public: from NIMBY to Participation*, Routledge.

Diana, JS et al. 2018, 'Responsible Aquaculture in 2050 : Valuing Local Conditions and Human Innovations Will Be Key to Success', , vol. 63, no. 4, pp. 255–262.

Diaz, RJ & Rosenberg, R 1995, 'Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna', *Oceanography and Marine Biology: an Annual Review*, vol. 33, pp. 245–303.

Diaz, RJ & Rosenberg, R 2008, 'Spreading dead zones and consequences for marine ecosystems.', *Science*, vol. 321, no. 5891, pp. 926–929.

Doney, SC et al. 2009, 'Ocean Acidification: The Other CO 2 Problem', *Annual Review of Marine Science*, vol. 1, no. 1, pp. 169–192.

Dudgeon, D et al. 2006, 'Freshwater biodiversity: importance, threats, status and conservation challenges', *Biological Reviews*, vol. 81, no. 02, p. 163.

Duhan, JS et al. 2017, 'Nanotechnology: The new perspective in precision agriculture', *Biotechnology Reports*, vol. 15, pp. 11–23.

Duke, NC et al. 2005, 'Herbicides implicated as the cause of severe mangrove dieback in the Mackay region, NE Australia: Consequences for marine plant habitats of the GBR World Heritage Area', *Marine Pollution Bulletin*, vol. 51, no. 1–4, pp. 308–324.

Dung, LC et al. 2009, 'Facilitating dialogue between aquaculture and agriculture: Lessons from role-playing games with farmers in the Mekong Delta, Vietnam', *Water Policy*, vol. 11, no. SUPPL. 1, pp. 80–93.

Dunn, DC et al. 2018, 'Empowering high seas governance with satellite vessel tracking data', *Fish and Fisheries*, vol. 19, no. 4, pp. 729–739.

Duru, M et al. 2015, 'How to implement biodiversity-based agriculture to enhance ecosystem services: a review', *Agronomy for sustainable development*, vol. 35, no. 4, pp. 1259–1281.

Edgar, GJ et al. 2014, ‘Global conservation outcomes depend on marine protected areas with five key features’, *Nature*, vol. 506, p. 216, <https://doi.org/10.1038/nature13022>.

Edwards, P 2015, ‘Aquaculture environment interactions: Past, present and likely future trends’, *Aquaculture*, vol. 447, pp. 2–14.

Ehrlich, PR & Harte, J 2015a, ‘Food security requires a new revolution’, *International Journal of Environmental Studies*, vol. 72, no. 6, pp. 908–920, <http://dx.doi.org/10.1080/00207233.2015.1067468>.

Ehrlich, PR & Harte, J 2015b, ‘Opinion : To feed the world in 2050 will require a global revolution’, *Proceedings of the National Academy of Science*, vol. 112, no. 48, pp. 1–2.

EIU 2018, *The Global Illicit Trade Environment Index.*

EM-DAT 2018, ‘The Emergency Events Database - Université catholique de Louvain (UCL) - CRED’, , p. www.emdat.be, Brussels, Belgium.

Emery, TJ et al. 2017, ‘Incorporating economics into fisheries management frameworks in Australia’, *Marine Policy*, vol. 77, pp. 136–143.

Essington, TE et al. 2015, ‘Fishing amplifies forage fish population collapses’, , vol. 112, no. 21.

FAO 1996, *Declaration on World Food Security. World Food Summit, FAO, Rome*.

FAO 2002, *FAO/WFP Crop and food supply assessment mission to Afghanistan. Global Information and Early Warning Systems on Food and Agriculture World Food Programme*.

FAO 2003, *National Aquaculture Sector Overview. Hungary. National Aquaculture Sector Overview Fact Sheets. Text by Varadi, L. In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 1 January 2003.*

FAO 2005a, *National Aquaculture Sector Overview. Morocco. National Aquaculture Sector Overview Fact Sheets. Text by Abdellatif, O.; El- Ahdal, M. In: FAO Fisheries and Aquaculture Department [online]. Rome.*

FAO 2005b, *Nutrition Country Profile - Republic of Albania. Food and Agricultural Organisation of the United Nations, Rome.*

FAO 2005c, *National Aquaculture Sector Overview. Ecuador. National Aquaculture Sector Overview Fact Sheets. Text by Schwarz, L. In: FAO Fisheries and Aquaculture Department [online]. Rome.*

FAO 2012, *The state of food and agriculture. Women in agriculture. Closing the gender gap for development*, FAO, Rome.

FAO 2015, *National Aquaculture Sector Overview. Albania. Text by Cobani, M. In: FAO Fisheries and Aquaculture Department [online]. Rome.*

FAO 2016, *The State of World Fisheries and Aquaculture 2016. Contributiing to food security and nutrition for all.*, The Food and Agricultural Organization of the United Nations. Rome.

FAO 2018, *State of World Fisheries and Aquaculture 2018 - Meeting Sustainable Development Goals*, Rome.

FAO 2019a, *FAOSTAT*, <http://www.fao.org/faostat/en/>.

FAO 2019b, ‘FishStatJ - Fisheries and aquaculture software for fisheries statistical time series’, , p. In: FAO Fisheries and Aquaculture Department, <http://www.fao.org/fishery/statistics/software/fishstatj/en>.

FAO IFAD UNICEF WFP & WHO 2017, *The State of Food Security and Nutrition in the World*.

FAO IFAD UNICEF WFP & WHO 2019, *The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns. Rome, FAO*.

FAO IFAD WFP 2015, *The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress*.

Farmery, AK et al. 2015, ‘Domestic or imported? An assessment of carbon footprints and sustainability of seafood consumed in Australia’, *Environmental Science and Policy*, vol. 54, pp. 35–43, <http://dx.doi.org/10.1016/j.envsci.2015.06.007>.

Farmery, AK et al. 2018, ‘Sociodemographic Variation in Consumption Patterns of Sustainable and Nutritious Seafood in Australia’, *Frontiers in Nutrition*, vol. 5, no. December, pp. 1–14.

Ficke, AD, Myrick, ÆCA, & Hansen, LJ 2007, *Potential impacts of global climate change on freshwater fisheries*.

Fisher, B et al. 2017, ‘Integrating fisheries and agricultural programs for food security’, *Agriculture & Food Security*, pp. 10–16.

Fleming, A et al. 2017, ‘The sustainable development goals: A case study’, *Marine Policy*, vol. 86, no. July, pp. 94–103.

Fluet-Chouinard, E, Funge-Smith, S, & McIntyre, PB 2018, ‘Global hidden harvest of freshwater fish revealed by household surveys’, *Proceedings of the National Academy of Sciences*, vol. 115, no. 29, pp. 7623–7628.

Foley, JA et al. 2011, ‘Solutions for a cultivated planet’, *Nature*, vol. 478, no. 7369, pp. 337–342.

Folke, C et al. 2004, ‘Regime Shifts, Resilience, and Biodiversity in Ecosystem Management’, *Annual Review of Ecology, Evolution, and Systematics*, vol. 35, no. 2004, pp. 557–581, <http://www.jstor.org/stable/30034127>.

Fontaneto, D et al. 2011, ‘Differences in fatty acid composition between aquatic and terrestrial insects used as food in human nutrition’, *Ecology of Food and Nutrition*, vol. 50, no. 4, pp. 351–367.

Føre, M et al. 2018, ‘Review Precision fish farming : A new framework to improve production in aquaculture’, *Biosystems Engineering*, vol. 173, pp. 176–193.

Francis, G, Makkar, HPS, & Becker, K 2001, *Antinutritional factors present in plant-derived alternate fish feed ingredients and their effects in fish*.

Fréon, P et al. 2014, ‘Harvesting for food versus feed: A review of Peruvian fisheries in a global context’, *Reviews in Fish Biology and Fisheries*, vol. 24, no. 1, pp. 381–398.

Froehlich, H, Gentry, RR, et al. 2017, ‘Public perceptions of aquaculture: Evaluating spatiotemporal patterns of sentiment around the world’, *PLoS ONE*, vol. 12, no. 1, pp. 1–18.

Froehlich, H, Jacobsen, N, et al. 2018, ‘Avoiding the ecological limits of forage fish for fed aquaculture’, *Nature Sustainability*, vol. 1, no. 6, pp. 298–303.

Froehlich, H, Runge, C, et al. 2018, ‘Comparative terrestrial feed and land use of an aquaculture-dominant world.’, *Proceedings of the National Academy of Sciences of the United States of America*, p. 201801692.

Froehlich, H, Gentry, Rebecca R, & Halpern, BS 2017, ‘Conservation aquaculture: Shifting the narrative and paradigm of aquaculture’s role in resource management’, *Biological conservation*, vol. 215, pp. 162–168.

Froese, R et al. 2016, ‘A critique of the balanced harvesting approach to fishing’, *ICES Journal of Marine Science*, vol. 73, pp. 1640–1650.

Fry, J et al. 2016, ‘The Environmental Health Impacts of Feeding Crops to Farmed Fish’, *Environment International*, vol. 91, pp. 201–214.

Fulton, EA et al. 2014, ‘An Integrated Approach Is Needed for Ecosystem Based Fisheries Management : Insights from Ecosystem-Level Management Strategy Evaluation’, *PloS one*, vol. 9, no. 1, p. e84242.

Galaz, V et al. 2015, ‘Why Ecologists Should Care about Financial Markets’, *Trends in Ecology and Evolution*, vol. 30, no. 10, pp. 571–580, <http://dx.doi.org/10.1016/j.tree.2015.06.015>.

Galloway, J et al. 2003, ‘The Nitrogen Cascade’, *BioScience*, vol. 53, no. 4, p. 341.

Galloway, J et al. 2010, ‘The impact of animal production systems on the nitrogen cycle’, *Livestock in a changing landscape*, vol. 1, pp. 83–96.

Garcia, SM et al. 2012, ‘Reconsidering the consequences of selective fisheries’, *Science*, vol. 335, no. 6072, pp. 1045–1047.

Garcia, SM & Cochrane, KL 2005, 'Ecosystem approach to fisheries: a review of implementation guidelines', *ICES Journal of Marine Science*, vol. 62, no. 3, pp. 311–318.

Garibaldi, LA et al. 2016, 'Farming Approaches for Greater Biodiversity , Livelihoods , and Food Security', *Trends in Ecology & Evolution*, vol. 32, no. 1, pp. 68–80, <http://dx.doi.org/10.1016/j.tree.2016.10.001>.

Garnett, T et al. 2013, 'Sustainable Intensifi cation in Agriculture: Premises and Policies', *Science Magazine*, vol. 341, pp. 33–34.

GBRMPA 2014, *Great Barrier Reef Marine Park Authority 2014, Great Barrier Reef Outlook Report 2014*, GBRMPA, Townsville.

Gebbers, R & Adamchuk, VI 2010, 'Precision Agriculture and Food Security', *Science*, vol. 327, no. 5967, pp. 828–831, <http://www.ncbi.nlm.nih.gov/pubmed/20150492%5Cnhttp://www.sciencemag.org/cgi/doi/10.1126/science.1183899>.

Gebrehiwot, M, Elbakidze, M, & Lidestav, G 2018, 'Gender relations in changing agroforestry homegardens in rural Ethiopia', *Journal of rural studies*, vol. 61, pp. 197–205.

Gemenne, F 2011, 'Climate-induced population displacements in a 4°C+ world.', *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, vol. 369, no. 1934, pp. 182–95.

Gende, S et al. 2002, 'Pacific Salmon in Aquatic and Terrestrial Ecosystems', *BioScience*, vol. 52, no. 10, pp. 917–928.

Gentry, RR et al. 2017, 'Mapping the global potential for marine aquaculture', *Nature*

Ecology and Evolution, vol. 1, no. 9, pp. 1317–1324, <http://dx.doi.org/10.1038/s41559-017-0257-9>.

Gephart, J et al. 2017, 'The "seafood-gap" in the food-water nexus literature — a review of methodologies and issues surrounding water use in seafood production chains', *Advances in Water Resources*, vol. 0, pp. 1–10, <http://dx.doi.org/10.1016/j.advwatres.2017.03.025>.

Gephart, J a, Pace, ML, & D'Odorico, P 2014, 'Freshwater savings from marine protein consumption', *Environmental Research Letters*, vol. 9, no. 1, p. 014005, <http://stacks.iop.org/1748-9326/9/i=1/a=014005>.

Gephart, JA et al. 2016, 'The environmental cost of subsistence: Optimizing diets to minimize footprints', *Science of the Total Environment*, vol. 553, pp. 120–127.

Gephart, Jessica A et al. 2017, 'Shocks to fish production: Identification, trends, and consequences', *Global Environmental Change*, vol. 42, pp. 24–32.

Gephart, JA, Froehlich, H, & Branch, TA 2019, 'Opinion: To create sustainable seafood industries, the United States needs a better accounting of imports and exports', *Proceedings of the National Academy of Sciences*, vol. 116, no. 19, pp. 9142–9146.

Van Gestel, LC, Kroese, FM, & De Ridder, DTD 2018, 'Nudging at the checkout counter–A longitudinal study of the effect of a food repositioning nudge on healthy food choice', *Psychology & health*, vol. 33, no. 6, pp. 800–809.

Gill, DA et al. 2017, 'Capacity shortfalls hinder the performance of marine protected areas globally', *Nature*, vol. 543, no. 7647, p. 665.

van Ginkel, M et al. 2013, 'An integrated agro-ecosystem and livelihood systems approach for the poor and vulnerable in dry areas', *Food Security*, vol. 5, no. 6, pp. 751–767.

GISTEMP 2019, *GISS Surface Temperature Analysis (GISTEMP)*, *NASA Goddard Institute for Space Studies*, viewed 11 November 2017, <https://data.giss.nasa.gov/gistemp/>.

Glover, K et al. 2013, 'Atlantic salmon populations invaded by farmed escapees: quantifying genetic introgression with a Bayesian approach and SNPs.', *BMC genetics*, vol. 14, p. 74, <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3765417&tool=pmcentrez&rendertype=abstract>.

Godfray, H, Beddington, J, et al. 2010, 'Food security: the challenge of feeding 9 billion people.', *Science*, vol. 327, no. 5967, pp. 812–8, <http://www.sciencemag.org/content/327/5967/812.abstract>.

Godfray, H, Crute, I, et al. 2010, 'The future of the global food system', *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, vol. 365, no. 1554, pp. 2769–2777.

Godfray, HCJ et al. 2018, 'Meat consumption, health, and the environment', *Science*, vol. 361, no. 6399, p. eaam5324.

Godfray, HCJ & Garnett, T 2014, 'Food security and sustainable intensification.', *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, vol. 369, no. 1639, p. 20120273.

Golden, CD et al. 2016, 'Fall in fish catch threatens human health', *Nature News*, vol. 534, no. 7607, pp. 317–320, <http://dx.doi.org/10.1038/534317a>.

Gorman, D, Russell, BD, & Connell, SD 2009, 'Land-to-sea connectivity: Linking human-derived terrestrial subsidies to subtidal habitat change on open rocky coasts', *Ecological Applications*, vol. 19, no. 5, pp. 1114–1126.

Goseberg, N et al. 2017,'Technological Approaches to Longlineand Cage-Based Aquaculture in Open Ocean Environments', in, *Aquaculture Perspective of Multi-Use Sites in the Open Ocean Bela H. Buck · Richard Langan Editors The Untapped Potential for Marine Resources in the Anthropocene*, pp.71–96.

Goucher, L et al. 2017, 'The environmental impact of fertilizer embodied in a wheat-to-bread supply chain', *Nature Plants*, vol. 3, no. 3, p. 17012.

Gowing, J, Tuong, T, & Hoanh, C 2006,'Environment and Livelihoods in Tropical Coastal Zones', in, *Environment and Livelihoods in Tropical Coastal Zones*, pp.1–16.

Hallstrom, E et al. 2019, 'Combined climate and nutritional performance of seafoods', *Journal of Cleaner Production*, vol. 230, pp. 402–411.

Halpern, B et al. 2019, 'Putting all foods on the same table: Achieving sustainable food systems requires full accounting', *Proceedings of the National Academy of Science*.

Halpern, BS, Lester, SE, & Mcleod, KL 2010, 'Placing marine protected areas onto the ecosystem- based management seascape', *Proceedings of the National Academy of Science*, vol. 107, no. 43, pp. 18312–18317.

Hamilton, HA et al. 2015, 'Investigating Cross-Sectoral Synergies through Integrated Aquaculture , Fisheries , A Case Study of Norway', *Journal of Industrial Ecology*, vol. 20, no. 4, pp. 867–882.

Harding, DJA et al. 2017, 'Migration patterns and estuarine aggregations of a catadromous fish , Australian bass (Percalates novemaculeata) in a regulated river system', *Marine and Freshwater Research*, vol. 68, pp. 1544–1553.

Harfoot, MBJ et al. 2014, 'Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model', *PLoS Biology*, vol. 12, no. 4.

Hasan, MR & Halwart, M 2009, *Fish as feed inputs for aquaculture: Practices, sustainability and implications*, <http://www.fao.org/docrep/field/003/ab825f/AB825F00.htm#TOC>.

Hazell, PBR & Hess, U 2010, 'Drought insurance for agricultural development and food security in dryland areas', *Food Security*, vol. 2, no. 4, pp. 395–405.

Heaney, S et al. 2001, 'Impacts of agriculture on aquatic systems: lessons learnt and new unknowns in Northern Ireland', *Marine And Freshwater Research*, vol. 52, pp. 151–163.

Henriksson, JPG et al. 2017, 'Indonesian aquaculture futures - Evaluating environmental and socioeconomic potentials and limitations', *Journal of Cleaner Production*, vol. 162, pp. 1482–1490, <http://dx.doi.org/10.1016/j.jclepro.2017.06.133>.

Henry, M et al. 2015, 'Review on the use of insects in the diet of farmed fish: Past and future', *Animal Feed Science and Technology*, vol. 203, no. 1, pp. 1–22.

Heron, T, Prado, P, & West, C 2018, 'Global Value Chains and the Governance of "Embedded" Food Commodities: The Case of Soy', *Global Policy*, vol. 9, no. October, pp. 29–37.

Hickey, LT et al. 2019, 'Breeding crops to feed 10 billion', *Nature Biotechnology*, <http://dx.doi.org/10.1038/s41587-019-0152-9>.

Hicks, CC et al. 2019, ‘Harnessing global fisheries to tackle micronutrient deficiencies’, *Nature*, vol. 574, no. 7776, pp. 95–98.

Hilborn, R et al. 2018, ‘The environmental cost of animal source foods’, *Frontiers in Ecology and the Environment*, pp. 329–335.

HLPE 2014, *Sustainable fisheries and aquaculture for food security and nutrition.*, Rome.

Hobday, AJ & Pecl, GT 2014, ‘Identification of global marine hotspots : sentinels for change and vanguards for adaptation action’, *Reviews in Fish Biology and Fisheries*, vol. 24, pp. 415–425.

Hochman, Z, Gobbett, DL, & Horan, H 2017, ‘Climate trends account for stalled wheat yields in Australia since 1990’, *Global change biology*, vol. 23, no. 5, pp. 2071–2081.

Hoekstra, AY & Mekonnen, M 2012, ‘The water footprint of food’, *Proceedings of the National Academy of Science*, vol. 109, no. 9, pp. 3232–3237.

Holm, P, Buck, B, & Langan, R 2017,‘Introduction: New Approaches to Sustainable Offshore Food Production and the Development of Offshore Platforms’, in, *Aquaculture Perspective of Multi-Use Sites in the Open Ocean The Untapped Potential for Marine Resources in the Anthropocene*, pp.1–22.

Houghton, RA 2012, ‘Carbon emissions and the drivers of deforestation and forest degradation in the tropics’, *Current Opinion in Environmental Sustainability*, vol. 4, no. 6, pp. 597–603.

Howarth, R & Paerl, HW 2008, ‘Coastal marine eutrophication: Control of both nitrogen and phosphorus is necessary.’, *Proceedings of the National Academy of Sciences of the United*

States of America, vol. 105, no. 49, pp. E103; author reply E104.

Hu, Z et al. 2012, 'Nitrous Oxide (N2O) Emission from Aquaculture : A Review', *Environmental Science and Technology*, vol. 46, pp. 6470–6480.

Hughes, TP et al. 2013, 'Multiscale regime shifts and planetary boundaries', *Trends in Ecology & Evolution*, vol. 28, no. 7.

van Huis, A 2011, 'Potential of Insects as Food and Feed in Assuring Food Security', *Annual Review of Entomology*, vol. 58, no. SEPTEMBER 2012, p. 120928130709004.

van Huis, A 2013, 'Potential of Insects as Food and Feed in Assuring Food Security', *Annual Review of Entomology*, vol. 58, no. 1, pp. 563–583.

Index Mundi 2019, *International Fishmeal and Fish Oil Organisation*.

IPCC 2019a,'Summary for Policy Makers', in PR Shukla et al. (eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

IPCC 2019b,'Summary for Policymakers.', in H-O Pörtner et al. (eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

Islam, SN & Gnauck, A 2008, 'Mangrove wetland ecosystems in Ganges-Brahmaputra delta in Bangladesh', *Frontiers of Earth Science in China*, vol. 2, no. 4, pp. 439–448.

Jackson, A & Shepherd, J 2010, 'Connections between farmed and wild fish: Fishmeal and fish oil as feed ingredients in sustainable aquaculture', *Advancing the Aquaculture Agenda:*

Workshop Proceedings, pp. 331–343.

Jacobsen, NS, Gislason, H, & Andersen, KH 2014, 'The consequences of balanced harvesting of fish communities.', *Proceedings. Biological sciences / The Royal Society*, vol. 281, no. 1775, p. 20132701.

Jennings, S 2005, 'Indicators to support an ecosystem approach to fisheries', *Fish and Fisheries*, vol. 6, no. 3, pp. 212–232.

Jennings, S et al. 2014, 'The ecosystem approach to fisheries: management at the dynamic interface between biodiversity conservation and sustainable use', *Annals of the New York Academy of Sciences*, vol. 1322, no. 1, pp. 48–60.

Jennings, S et al. 2016, 'Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment', *Fish and Fisheries*, vol. 17, pp. 893–938.

Jonsson, B & Jonsson, N 2006, 'Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish', *ICES Journal of Marine Science*, vol. 63, no. 7, pp. 1162–1181.

Jusoff, K & Bin Hj Taha, DHD 2008, 'Managing Sustainable Mangrove Forests in Peninsular Malaysia', *Journal of Sustainable Development*, vol. 1, no. 1, pp. 88–96.

Kato, T, Kuroda, H, & Nakasone, H 2009, 'Runoff characteristics of nutrients from an agricultural watershed with intensive livestock production', *Journal of Hydrology*, vol. 368, no. 1–4, pp. 79–87.

Kelley, CP et al. 2015, 'Climate change in the Fertile Crescent and implications of the recent

Syrian drought', *Proceedings of the National Academy of Sciences*, vol. 112, no. 11, pp. 3241–3246.

Kennedy, K et al. 2012, 'Long term monitoring of photosystem II herbicides - Correlation with remotely sensed freshwater extent to monitor changes in the quality of water entering the Great Barrier Reef, Australia', *Marine Pollution Bulletin*, vol. 65, no. 4–9, pp. 292–305, <http://dx.doi.org/10.1016/j.marpolbul.2011.10.029>.

Khan, ZR et al. 2014, 'Achieving food security for one million sub-Saharan African poor through push-pull innovation by 2020', *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 369, no. 1639, pp. 20120284–20120284.

Kimenyi, M et al. 2014, *The Impact of Conflict and Political Instability on Agricultural Investments in Mali and Nigeria. Afrca Growth Initiative. Working Paper 17.*

Kiptot, E, Franzel, S, & Degrande, A 2014, 'Gender, agroforestry and food security in Africa', *Current Opinion in Environmental Sustainability*, vol. 6, pp. 104–109.

Kirchhoff, NT, Rough, KM, & Nowak, BF 2011, 'Moving cages further offshore: Effects on southern bluefin tuna, T. maccoyii, parasites, health and performance', *PLoS ONE*, vol. 6, no. 8, pp. 6–13.

Kleitou, P, Kletou, D, & David, J 2018, 'Is Europe ready for integrated multi-trophic aquaculture ? A survey on the perspectives of European farmers and scientists with IMTA experience', *Aquaculture*, vol. 490, no. November 2017, pp. 136–148.

Klinger, D & Naylor, R 2012, 'Searching for Solutions in Aquaculture: Charting a Sustainable Course', *Annual Review of Environment and Resources*, vol. 37, pp. 247–276.

Kokou, F & Fountoulaki, E 2018, ‘Aquaculture waste production associated with antinutrient presence in common fi sh feed plant ingredients’, *Aquaculture*, vol. 495, no. January, pp. 295–310.

Kovac-Hostyanszki, A et al. 2017, ‘Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination’, *Ecology Letters*, vol. 20, pp. 673–689.

Kristofersson, D & Anderson, JL 2006, ‘Is there a relationship between fisheries and farming? Interdependence of fisheries, animal production and aquaculture’, *Marine Policy*, vol. 30, no. 6, pp. 721–725.

Lafferty, KD et al. 2015, ‘Infectious Diseases Affect Marine Fisheries and Aquaculture Economics’, *Annual Review of Marine Science*, vol. 7, pp. 471–96.

Laffoley, D & Baxter, J (editors) 2016, *Explaining Ocean Warming: Causes, scales, effects and consequences. Full report*, Gland, Switzerland: IUCN.

Lam, VWY et al. 2016, ‘Projected change in global fisheries revenues under climate change’, *Nature Publishing Group*, pp. 6–13.

Lambin, EF & Meyfroidt, P 2011, ‘Global land use change, economic globalization, and the looming land scarcity’, *Proceedings of the National Academy of Sciences*, vol. 108, no. 9, pp. 3465–3472.

Lehner, M, Mont, O, & Heiskanen, E 2016, ‘Nudging – A promising tool for sustainable consumption behaviour?’, *Journal of Cleaner Production*, vol. 134, pp. 166–177, <http://dx.doi.org/10.1016/j.jclepro.2015.11.086>.

Lehnert, SJ, Heath, JW, & Heath, DD 2013, ‘Ecological and genetic risks arising from reproductive interactions between wild and farmed Chinook salmon’, *Canadian Journal of Fisheries and Aquatic Science*, vol. 70, no. August, pp. 1691–1698.

Lemly, AD, Kingsford, RT, & Thompson, JR 2000, ‘Irrigated agriculture and wildlife conservation: Conflict on a global scale’, *Environmental Management*, vol. 25, no. 5, pp. 485–512.

Lenssen, NJL et al. 2019, ‘Improvements in the uncertainty model in the Goddard Institute for Space Studies Surface Temperature (GISTEMP) analysis’, *Journal of Geophysical Research: Atmospheres*.

Lesk, C, Rowhani, P, & Ramankutty, N 2016, ‘Influence of extreme weather disasters on global crop production’, *Nature*, vol. 529, no. 7584, pp. 84–87.

Lester, SE et al. 2018, ‘Marine spatial planning makes room for offshore aquaculture in crowded coastal waters’, *Nature Communications*, pp. 1–13, <http://dx.doi.org/10.1038/s41467-018-03249-1>.

Lewis, SE et al. 2012, ‘Assessing the additive risks of PSII herbicide exposure to the Great Barrier Reef’, *Marine Pollution Bulletin*, vol. 65, no. 4–9, pp. 280–291.

Link, JS 2002, ‘What Does Ecosystem-Based Fisheries Management Mean ?’, *Fisheries*, vol. 24, no. 4, pp. 18–21.

Liu, J et al. 2013, ‘Framing Sustainability in a Telecoupled World’, *Ecology and Society*, vol. 2, no. 26.

Liu, W et al. 2018, ‘A novel agricultural photovoltaic system based on solar spectrum separation’, *Solar Energy*, vol. 162, pp. 84–94.

Liu, Y et al. 2016, ‘Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater’, *Aquacultural Engineering*, vol. 71, pp. 1–12.

Llagostera, PF et al. 2019, ‘The use of insect meal as a sustainable feeding alternative in aquaculture : Current situation , Spanish consumers ’ perceptions and willingness to pay’, *Journal of Cleaner Production*, vol. 229, pp. 10–21, <https://doi.org/10.1016/j.jclepro.2019.05.012>.

Lundy, ME & Parrella, MP 2015, ‘Crickets are not a free lunch: Protein capture from scalable organic side-streams via high-density populations of Acheta domesticus’, *PLoS ONE*, vol. 10, no. 4, pp. 1–12.

Luo, Z, Hu, S, & Chen, D 2018, ‘The trends of aquacultural nitrogen budget and its environmental implications in China’, *Scientific Reports*, , no. July, pp. 1–9, <http://dx.doi.org/10.1038/s41598-018-29214-y>.

Mahan, KM et al. 2018, ‘Production of single cell protein from agro-waste using Rhodococcus opacus’, *Journal of Industrial Microbiology and Biotechnology*, , no. 0123456789, pp. 1–7.

Mahlein, A-K 2016, ‘Plant disease detection by imaging sensors–parallels and specific demands for precision agriculture and plant phenotyping’, *Plant disease*, vol. 100, no. 2, pp. 241–251.

Maia, MRG et al. 2016, ‘The Potential Role of Seaweeds in the Natural Manipulation of Rumen Fermentation and Methane Production’, *Nature: Scientific Reports*, vol. 6, no.

August, p. 32321.

Marchand, P et al. 2016, ‘Reserves and trade jointly determine exposure to food supply shocks’, *Environmental Research Letters*, vol. 11, no. 9.

Marshall, A 2014, ‘Drought-tolerant varieties begin global march’, *Nature Biotechnology*, vol. 32, no. 4, pp. 308–308.

Marzloff, MP et al. 2016, ‘Modelling marine community responses to climate-driven species redistribution to guide monitoring and adaptive ecosystem-based management’, *Global Change Biology*, vol. 22, no. 7, pp. 2462–2474.

Mascia, MB, Claus, CA, & Naidoo, R 2010, ‘Impacts of Marine Protected Areas on Fishing Communities’, *Conservation Biology*, vol. 24, no. 5, pp. 1424–1429.

Matthews, A 2014, ‘Trade rules, food security and the multilateral trade negotiations’, *European Review of Agricultural Economics*, vol. 41, no. 3, pp. 511–535.

Mayaux, P et al. 2005, ‘Tropical forest cover change in the 1990s and options for future monitoring’, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 360, no. 1454, pp. 373–384.

Mazur, NA & Curtis, AL 2008, ‘Understanding community perceptions of aquaculture: Lessons from Australia’, *Aquaculture International*, vol. 16, no. 6, pp. 601–621.

McCarthy, U et al. 2018, ‘Global food security–Issues, challenges and technological solutions’, *Trends in Food Science & Technology*, vol. 77, pp. 11–20.

Mengerink, KJ et al. 2014, ‘A Call for Deep-Ocean Stewardship’, *Science*, vol. 344, no.

6185, pp. 696–698.

Merino, G et al. 2012, ‘Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate?’, *Global Environmental Change*, vol. 22, no. 4, pp. 795–806.

Messmer, V et al. 2016, ‘Global warming will disproportionately affect larger adults in a predatory coral reef fish’, *Global Change Biology*, pp. 1–11.

Metian, M et al. 2019, ‘Mapping diversity of species in global aquaculture’, *Reviews in Aquaculture*, pp. 1–11.

Midtbo, LK et al. 2015, ‘Intake of farmed Atlantic salmon fed soybean oil increases hepatic levels of arachidonic acid-derived oxylipins and ceramides in mice’, *Journal of Nutritional Biochemistry*, vol. 26, no. 6, pp. 585–595.

Mohan, P 2017, ‘The economic impact of hurricanes on bananas: A case study of Dominica using synthetic control methods’, *Food Policy*, vol. 68, pp. 21–30, <http://dx.doi.org/10.1016/j.foodpol.2016.12.008>.

Mosby, D 2018, *Australian fisheries and aquaculture statistics 2017, Fisheries Research and Development Corporation project 2018-134, ABARES, Canberra, December. CC BY 4.0.*

Moutopoulos, D, Bradshaw, B, & Pauly, D 2015, ‘Reconstruction of Albania fishery catches by fishing gear’, *Fisheries Centre Working Paper Series*, vol. 12.

Msuya, F 2006, ‘The impact of seaweed farming on the social and economic structure of seaweed farming communities in Zanzibar, Tanzania’, *World seaweed resources, Version*, vol. 1, p. 27.

Myhre, G et al. 2013,‘Anthropogenic and Natural Radiative Forcing’, in T Stocker et al. (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernemental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.659–740.

Nakamura, K et al. 2018, ‘Seeing slavery in seafood supply chains’, *Science advances*, vol. 4, no. 7, p. e1701833.

Nam, KC, Jo, C, & Lee, M 2010, ‘Meat products and consumption culture in the East’, *Meat Science*, vol. 86, no. 1, pp. 95–102.

Napier, JA, Olsen, R-E, & Tocher, D 2019, ‘Update on GM canola crops as novel sources of omega-3 fish oils’, *Plant Biotechnology Journal*, vol. 17, pp. 703–705.

Nash, KL et al. 2017, ‘Planetary boundaries for a blue planet’, *Nature ecology & evolution*, vol. 1, no. 11, p. 1625.

Natale, F et al. 2013, ‘Interactions between aquaculture and fisheries’, *Marine Policy*, vol. 38, no. March 2016, pp. 205–213.

Naylor, R et al. 2000a, ‘Effect of aquaculture on world fish supplies.’, *Nature*, vol. 405, pp. 1017–1024.

Naylor, R et al. 2000b, ‘Effect of aquaculture on world fish supplies.’, *Nature*, vol. 405, no. 6790, pp. 1017–1024.

Naylor, R et al. 2005, ‘Losing the Links Between Livestock and Land’, *Science*, , no. December, pp. 1621–1622.

Naylor, R et al. 2009, ‘Feeding aquaculture in an era of finite resources’, *Proceedings of the National Academy of Sciences*, vol. 106, no. 42, pp. 15103–15110.

Naylor, R, Williams, SL, & Strong, DR 2001, ‘Aquaculture - A gateway for exotic species’, *Science*, vol. 294, no. November, pp. 1655–1666.

Naylor, RL & Burke, M 2005, ‘Aquaculture and Ocean Resoources: Raising Tigers of the Sea’, *Annual Review of Environment and Resources*, vol. 30, no. 1, pp. 185–218.

Nelson, GC et al. 2014, ‘Climate change effects on agriculture: economic responses to biophysical shocks.’, *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, no. 9, pp. 3274–9.

Neset, TSS & Cordell, D 2012, ‘Global phosphorus scarcity: Identifying synergies for a sustainable future’, *Journal of the Science of Food and Agriculture*, vol. 92, no. 1, pp. 2–6.

Newbold, T et al. 2015, ‘Global effects of land use on local terrestrial biodiversity’, *Nature*, vol. 520, no. 7545, pp. 45–50.

Newton, P et al. 2007, *Fishery Economic Status Report, ABARE Report 07.19 Prepared for the Fisheries Resources Research Fund, Canberra, October.*

Noland, M 2004, ‘Famine and Reform in North Korea’, *Asian Economic Papers*, vol. 3, no. 2, pp. 1–40.

Noland, M, Robinson, S, & Wang, T 2001, ‘Famine in North Korea: Causes and Cures’, *Economic Development and Cultural Change*, vol. 49, no. 4, pp. 741–767.

Nunes, JP et al. 2011, ‘Towards an ecosystem approach to aquaculture: assessment of sustainable shellfish cultivation at different scales of space, time and complexity', *Aquaculture*, vol. 315, no. 3–4, pp. 369–383.

Oonincx, DGAB et al. 2010, 'An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption', *PLoS ONE*, vol. 5, no. 12, pp. 1–7.

Oonincx, DGAB & de Boer, IJM 2012, 'Environmental Impact of the Production of Mealworms as a Protein Source for Humans - A Life Cycle Assessment', *PLoS ONE*, vol. 7, no. 12, pp. 1–5.

Osmundsen, TC et al. 2020, 'The operationalisation of sustainability : Sustainable aquaculture production as defined by certification schemes', *Global Environmental Change*, vol. 60, no. December 2019, p. 102025.

Österblom, H et al. 2016, 'Marine Ecosystem Science on an Intertwined Planet', *Ecosystems*, vol. 20, no. 1, pp. 54–61.

Ostrom, E 2009, 'A general framework for analyzing sustainability of social-ecological systems', *Science*, vol. 325, no. July, pp. 419–422.

Øverland, M & Skrede, A 2017, 'Yeast derived from lignocellulosic biomass as a sustainable feed resource for use in aquaculture', *Journal of the Science of Food and Agriculture*, , no. October.

Pahlow, M et al. 2015, 'Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production', *Science of the Total Environment*, vol. 536, pp. 847–857.

Paul, A & Roskaft, E 2013, ‘Environmental degradation and loss of traditional agriculture as two causes of conflicts in shrimp farming in the southwestern coastal Bangladesh: Present status and probable solutions’, *Ocean and Coastal Management*, vol. 85, pp. 19–28.

Paul, B & Vogl, C 2011, ‘Impacts of shrimp farming in Bangladesh: Challenges and alternatives’, *Ocean and Coastal Management*, vol. 54, no. 3, pp. 201–211.

Pauly, D 1994, ‘From growth to malthusian overfishing : Stages of fisheries resources misuse’, *Traditional Marine Resource Management and Knowledge Information Bulletin, South Pacific Commission*, , no. January, pp. 7–14.

Pauly, D & Zeller, D 2016, ‘Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining’, *Nature Communications*, vol. 7, pp. 1–9.

Pecl, GT et al. 2014, ‘Rapid assessment of fisheries species sensitivity to climate change’, *Climatic Change*, vol. 127, no. 3–4, pp. 505–520.

Pelletier, N et al. 2011, ‘Energy Intensity of Agriculture and Food Systems’, *Annual Review of Environment and Resources*, vol. 36, pp. 223–46.

Pelletier, N et al. 2018, ‘Nutritional Attributes, Substitutability, Scalability, and Environmental Intensity of an Illustrative Subset of Current and Future Protein Sources for Aquaculture Feeds: Joint Consideration of Potential Synergies and Trade-offs’, *Environmental Science and Technology*, vol. 52, no. 10, pp. 5532–5544.

Periyasamy, C, Anantharaman, P, & Balasubramanian, T 2014, ‘Social upliftment of coastal fisher women through seaweed (Kappaphycus alvarezii (Doty) Doty) farming in Tamil Nadu , India’, *Journal of Applied Phycology*, vol. 26, pp. 775–781.

Perry, BD, Grace, D, & Sones, K 2013, ‘Current drivers and future directions of global livestock disease dynamics’, *Proceedings of the National Academy of Sciences*, vol. 110, no. 52, pp. 20871–20877, <http://www.pnas.org/cgi/doi/10.1073/pnas.1012953108>.

Phalan, B et al. 2016, ‘How can higher-yield farming help to spare nature?’, *Science*, vol. 351, no. 6272, pp. 450–451.

Pickering, C & Byrne, J 2014, ‘The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers’, *Higher Education Research and Development*, vol. 33, no. 3, pp. 534–548.

Pikitch, EK et al. 2004, ‘Ecosystem-based Fishery Management’, *Science Policy Forum*, vol. 305, pp. 346–347.

Piontek, F et al. 2014, ‘Multisectoral climate impact hotspots in a warming world.’, *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, no. 9, pp. 3233–8.

Pitcher, T et al. 2009, ‘Not honouring the code’, *Nature*, vol. 457, no. 7230, p. 658.

Pittelkow, CM et al. 2015, ‘Productivity limits and potentials of the principles of conservation agriculture’, *Nature*, vol. 517, no. January, pp. 365–368.

Pittman, J & Armitage, D 2016, ‘Governance across the land-sea interface: A systematic review’, *Environmental Science & Policy*, vol. 64, pp. 9–17.

Poore, J & Nemecek, T 2018, ‘Reducing food ’ s environmental impacts through producers and consumers’, *Science*, vol. 360, no. June, pp. 987–992.

Popkin, BM, Adair, LS, & Ng, SW 2012, ‘Global nutrition transition and the pandemic of obesity in developing countries’, *Nutrition Reviews*, vol. 70, pp. 3–21.

Prein, M 2002, ‘Integration of aquaculture into crop–animal systems in Asia’, *Agricultural Systems*, vol. 71, no. 1–2, pp. 127–146.

Pretty, JN 1997, ‘The sustainable intensification of agriculture’, *Natural Resources Forum*, vol. 21, no. 97, pp. 247–256.

Primavera, JH 2006, ‘Overcoming the impacts of aquaculture on the coastal zone’, *Ocean and Coastal Management*, vol. 49, no. 9–10, pp. 531–545.

Puma, MJ et al. 2015, ‘Assessing the evolving fragility of the global food system’, *Environmental Research Letters*, vol. 10, no. 2.

R Core Development Team 2017, ‘A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.’, , p. https://www.R-project.org/.

Rabalais, NN 2002, ‘Nitrogen in aquatic ecosystems.’, *Ambio*, vol. 31, no. 2, pp. 102–112.

Ramdeen, R, Harper, S, & Zeller, D 2014, ‘Reconstruction of total marine fisheries catches for Dominica (1950-2010)’, *Fisheries Catch Reconstructions: Islands, Part IV. Fisheries Centre Research Reports. Sea Around Us Fisheries Centre, University of Bristish Columbia*, vol. 22(2), pp. 33–41.

Rao, MP et al. 2015, ‘Dzuds, droughts, and livestock mortality in Mongolia’, *Environmental Research Letters*, vol. 10, no. 7.

Ratcliff, JJ et al. 2016, ‘Metal content of kelp (Laminaria digitata) co-cultivated with Atlantic salmon in an Integrated Multi-Trophic Aquaculture system', *Aquaculture*, vol. 450, pp. 234–243.

Reisch, LA, Sunstein, CR, & Gwozdz, W 2017, 'Viewpoint : Beyond carrots and sticks : Europeans support health nudges', *Food Policy*, vol. 69, pp. 1–10, <http://dx.doi.org/10.1016/j.foodpol.2017.01.007>.

Renard, D & Tilman, D 2019, 'National food production stabilized by crop diversity', *Nature*, vol. 571, no. 7764, pp. 257–260.

Renaud 1986, 'Hypoxia in Louisiana coastal waters during 1983: Implications for fisheries.', *U S National Marine Fisheries Service Fishery Bulletin*, vol. 84, no. 1, pp. 19–26.

Reuter, K, Juhn, D, & Grantham, H 2016, 'Integrated land-sea management: Recommendations for planning, implementation, and management', , , no. 2.

Rhein, M et al. 2013,'Observations: Ocean', in TF Stocker et al. (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernemental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Richards, DR & Friess, DA 2015, 'Rates and drivers of mangrove deforestation in Southeast Asia, 2000-2012', *Proceedings of the National Academy of Science*, vol. 113, no. 2, pp. 344–349.

Riley, H & Buttriss, JL 2011, 'A UK public health perspective : what is a healthy sustainable diet ?', *Nutrition Bulletin*, pp. 426–431.

Roberge, C et al. 2008, 'Genetic consequences of interbreeding between farmed and wild

Atlantic salmon: Insights from the transcriptome', *Molecular Ecology*, vol. 17, no. 1, pp. 314–324.

Rockström, J et al. 2009, 'A safe operating space for humanity', *Nature*, vol. 461, no. September, pp. 472–475.

Rosas, VT et al. 2018, 'Feasibility of the use of Spirulina in aquaculture diets', *Reviews in Aquaculture*, pp. 1–12.

Rose, D 2018, 'Environmental nudges to reduce meat demand', *The Lancet Planetary Health*, vol. 2, no. 9, pp. e374–e375.

Rosenzweig, C et al. 2014, 'Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison.', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, no. 9, pp. 3268–73, <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3948251&tool=pmcentrez&rendertype=abstract>.

Rousseau, Y et al. 2019, 'Evolution of global marine fishing fleets and the response of fished resources', *Proceedings of the National Academy of Science*, vol. 116, no. 25, pp. 12238–12243.

Rulli, C, Saviori, A, & D'Odorico, P 2012, 'Global land and water grabbing', *Proceedings of the National Academy of Sciences*, vol. 110, no. 3, pp. 892–897.

Rummer, JL & Munday, PL 2017, 'Climate change and the evolution of reef fishes: Past and future', *Fish and Fisheries*, vol. 18, pp. 22–39.

Sachs, J et al. 2018, *SDG Index and Dashboards Report 2018. New York: Bertelsmann*

Stiftung and Sustainable Development Solutions Network (SDSN).

Sanchez-Muros, M-J, Barroso, F, & Manzano-Agugliaro, F 2014, 'Insect meal as renewable source of food for animal feeding: A review', *Journal of Cleaner Production*, vol. 65, pp. 16–27.

Sarch, M-T 1996, 'Fishing and Farming at Lake Chad: Overcapitalisation, Opportunities and Fisheries Management', *Journal of Environmental Management*, vol. 48, no. 4, pp. 305–320.

Sartori, M & Schiavo, S 2015, 'Connected we stand: A network perspective on trade and global food security', *Food Policy*, vol. 57, pp. 114–127.

Sasson, Albert et al. 2012, 'Food security for Africa: an urgent global challenge', *Agriculture & Food Security*, vol. 1, no. 1, p. 2.

Scheffer, M et al. 2012, 'Anticipating critical transitions', *Science*, vol. 338, no. 6105, pp. 344–348.

Schipanski, ME et al. 2016, 'Realizing resilient food systems', *BioScience*, vol. 66, no. 7, pp. 600–610.

Schmidhuber, J & Tubiello, FN 2007, *Global food security under climate change*, Washington DC.

Sealey, WM et al. 2011, 'Sensory Analysis of Rainbow Trout, Oncorhynchus mykiss, Fed Enriched Black Soldier Fly Prepupae, Hermetia illucens', *Journal of the World Aquaculture Society*, vol. 42, no. 1, pp. 34–45.

Seekell, D et al. 2017, 'Resilience in the global food system', *Environmental Research*

Letters, vol. 12, p. 025010.

Seifert, F 2008, ‘Consensual NIMBYs, Contentious NIABYs : Explaining Contrasting Forms of Farmers GMO Opposition in Austria and France’, *European Society for Rural Sociology*, vol. 49, no. 1, pp. 20–40.

Selkoe, KA et al. 2015, ‘Principles for managing marine ecosystems prone to tipping points’, *Ecosystem Health and Sustainability*, vol. 1, no. 5, p. art17.

Sen, A 1981, *Poverty and famines: an essay on entitlement and deprivation*, Oxford university press.

Shah, MR et al. 2018, ‘Microalgae in aquafeeds for a sustainable aquaculture industry’, *Journal of Applied Phycology*, vol. 30, no. 1, pp. 197–213.

Sharma, N et al. 2016, ‘Bioenergy from agroforestry can lead to improved food security , climate change , soil quality , and rural development’, *Food and Energy Security*, vol. 5, no. 3, pp. 165–183.

Shepherd, CJ & Jackson, AJ 2013, ‘Global fishmeal and fish-oil supply: Inputs, outputs and marketsa’, *Journal of Fish Biology*, vol. 83, no. 4, pp. 1046–1066.

Sibanda, S & Workneh, TS 2019, ‘Effects of indirect air cooling combined with direct evaporative cooling on the quality of stored tomato fruit’, *CyTA-Journal of Food*, vol. 17, no. 1, pp. 603–612.

De Silva, S & Soto, D 2009,‘Climate change and aquaculture: potential impacts, adaptation and mitigation’, in K Cochrane et al. (eds.), *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture*

Technical Paper. No. 530., FAO, Rome, pp.151–212.

Simopoulos, AP 2002, 'The importance of the ratio of omega-6/omega-3 essential fatty acids', *Biomedicine & Pharmacotherapy*, vol. 56, no. 8, pp. 365–379.

Siple, MC, Essington, TE, & E. Plagányi, É 2019, 'Forage fish fisheries management requires a tailored approach to balance trade-offs', *Fish and Fisheries*, vol. 20, no. 1, pp. 110–124.

Skjæraasen, JE et al. 2010, 'Mating competition between farmed and wild cod Gadus morhua', *Marine Ecology Progress Series*, vol. 412, pp. 247–258.

Skretting 2015, *Annual sustainability report 2015, Skretting Australia*, <http://www.jbsglobal.com/sites/default/files/jbs_ras_2013_ing.pdf>.

Skretting 2017, *Sustainability report. Global 2017*.

Skretting 2019, *Skretting continues implementation of novel raw materials in feed*, , p. https://www.skretting.com/en/news/news/skretting-c.

Skretting Australia 2016, *Fishmeal-free breakthrough for Skretting*, *News, Events and Publications*, <http://www.skretting.com/en-AU/news-events-and-publications/news/fishmeal-free-breakthrough-for-skretting/1117274>.

Smil, V 2002, 'Nitrogen and Food Production: Proteins for Human Diets', *AMBIO: A Journal of the Human Environment*, vol. 31, no. 2, p. 126.

Smith, ADM et al. 2011, 'Impacts of Fishing Low–Trophic Level Species on Marine Ecosystems', *Science*, vol. 333, no. August, pp. 1147–1150.

Smith, MD et al. 2010, ‘Genetically modified salmon and full impact assessment’, *Science*, vol. 330, no. 6007, pp. 1052–1053.

Smith, P et al. 2014,‘Agriculture, Forestry and Other Land Use (AFOLU)’, in O Edenhofer et al. (eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessmnet of Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.811–922.

Smith, P 2018, ‘Managing the global land resource’, *Proceedings of the Royal Society B: Biological Sciences*, vol. 285, no. 1874, p. 20172798.

Sonesson, U, Davis, J, & Ziegler, F 2010, *Food Production and Emissions of Greenhouse Gases: An overview of the climate impact of different product groups. The Swedish Institute for Food and Biotechnology. SIK Report. No 802. 2010*.

Soto, D et al. 2008, ‘Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures’, *Building an ecosystem approach to aquaculture*, vol. 14.

Sprague, M et al. 2015, ‘Replacement of fish oil with a DHA-rich algal meal derived from Schizochytrium sp. on the fatty acid and persistent organic pollutant levels in diets and flesh of Atlantic salmon (Salmo salar, L.) post-smolts’, *Food Chemistry*, vol. 185, pp. 413–421.

Sprague, M, Betancor, MB, & Tocher, DR 2017, ‘Microbial and genetically engineered oils as replacements for fish oil in aquaculture feeds’, *Biotechnology Letters*, vol. 39, no. 11, pp. 1599–1609.

Springmann, M et al. 2016, ‘Analysis and valuation of the health and climate change cobenefits of dietary change', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 113, no. 15, pp. 4146–4151.

Springmann, M et al. 2018, 'Options for keeping the food system within environmental limits', *Nature*, , no. October.

Steffen, W et al. 2015, 'Planetary boundaries: Guiding human development on a changing planet', *Science (New York, N.Y.)*, vol. 348, no. 6240, p. 1217.

Stenberg, JA 2017, 'A Conceptual Framework for Integrated Pest Management', *Trends in Plant Science*, vol. 22, no. 9, pp. 759–769, <http://dx.doi.org/10.1016/j.tplants.2017.06.010>.

Stentiford, GD et al. 2012, 'Disease will limit future food supply from the global crustacean fishery and aquaculture sectors', *Journal of Invertebrate Pathology*, vol. 110, no. 2, pp. 141–157, <http://dx.doi.org/10.1016/j.jip.2012.03.013>.

Stentiford, GD et al. 2017, 'New Paradigms to Help Solve the Global Aquaculture Disease Crisis', *PLoS Pathogens*, vol. 13, no. 2, pp. 1–6.

Stoner, GR et al. 1990, 'Effect of select menhaden fish meal in starter diets for pigs.', *Journal of animal science*, vol. 68, no. 9, pp. 2729–2735.

Sumaila, U et al. 2015, 'Winners and losers in a world where the high seas is closed to fishing', *Scientific Reports*, vol. 5, p. 8481.

Sumaila, UR et al. 2011, 'economics of world fisheries', *Nature Climate Change*, vol. 1, no. 9, pp. 449–456.

Suttle, K, Thomsen, M, & Power, M 2007, 'Species Interactions Reverse Grassland

Responses to Changing CLimate’, *Science*, vol. 315, no. 5812, pp. 640–642.

Suweis, S et al. 2015, ‘Resilience and reactivity of global food security’, *Proceedings of the National Academy of Sciences*, vol. 112, no. 34, pp. E4811–E4811.

Tacon, A & Metian, M 2009, ‘Fishing for Aquaculture: Non-Food Use of Small Pelagic Forage Fish—A Global Perspective’, *Reviews in Fisheries Science*, vol. 17, no. 3, pp. 305–317.

Tacon, A & Metian, M 2015, ‘Feed Matters: Satisfying the Feed Demand of Aquaculture’, *Reviews in Fisheries Science & Aquaculture*, vol. 23, no. 1, pp. 1–10.

Tacon, AGJ, Hasan, MR, & Metian, M 2011, *Demand and supply of feed ingredients for farmed fish and crustaceans : Trends and prospects*.

Tacon, AGJ & Metian, M 2008, ‘Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects’, *Aquaculture*, vol. 285, no. 1–4, pp. 146–158.

Tadesse, G et al. 2014, ‘Drivers and triggers of international food price spikes and volatility’, *Food Policy*, vol. 47, pp. 117–128.

Taelman, SE et al. 2013, ‘Bioresource Technology The environmental sustainability of microalgae as feed for aquaculture : A life cycle perspective’, , vol. 150, pp. 513–522.

Tallis, H, Ferdaña, Z, & Gray, E 2008, ‘Linking terrestrial and marine conservation planning and threats analysis’, *Conservation Biology*, vol. 22, no. 1, pp. 120–130.

Tassal 2018, ‘Tassal kelp culturing program in Southeast Tasmania progressing well’, *Tassal Group Ltd Media Release*, pp. 1–2.

Tickler, D, Meeuwig, JJ, Palomares, M-L, et al. 2018, ‘Far from home: Distance patterns of global fishing fleets’, *Science advances*, vol. 4, no. 8, p. eaar3279.

Tickler, D, Meeuwig, JJ, Bryant, K, et al. 2018, ‘Modern slavery and the race to fish’, *Nature communications*, vol. 9, no. 1, p. 4643.

Tiller, R, Brekken, T, & Bailey, J 2012, ‘Norwegian aquaculture expansion and Integrated Coastal Zone Management (ICZM): Simmering conflicts and competing claims’, *Marine Policy*, vol. 36, no. 5, pp. 1086–1095, <http://dx.doi.org/10.1016/j.marpol.2012.02.023>.

Tilman, D et al. 2002, ‘Agricultural sustainability and intensive production practices’, *Nature*, vol. 418, no. 6898, pp. 671–677.

Tilman, D et al. 2011, ‘Global food demand and the sustainable intensification of agriculture.’, *Pnas*, vol. 108, no. 50, pp. 20260–4, <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3250154&tool=pmcentrez&rendertype=abstract>.

Tilman, D & Clark, M 2014, ‘Global diets link environmental sustainability and human health.’, *Nature*, vol. 515, no. 7528, pp. 518–522.

Troell, M et al. 2009, ‘Ecological engineering in aquaculture - Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems’, *Aquaculture*, vol. 297, no. 1–4, pp. 1–9.

Troell, M, Naylor, RL, et al. 2014, ‘Does aquaculture add resilience to the global food system?’, *Proceedings of the National Academy of Sciences*, vol. 111, no. 37, pp. 13257–

13263.

Troell, M, Metian, M, et al. 2014, ‘Comment on “Water footprint of marine protein consumption—aquaculture’s link to agriculture”’, *Environmental Research Letters*, vol. 9, no. 10, p. 109001.

Turchini, GM, Torstensen, BE, & Ng, WK 2009, ‘Fish oil replacement in finfish nutrition’, *Reviews in Aquaculture*, vol. 1, no. 1, pp. 10–57.

Turchini, GM, Trushenski, JT, & Glencross, BD 2019, ‘Thoughts for the Future of Aquaculture Nutrition: Realigning Perspectives to Reflect Contemporary Issues Related to Judicious Use of Marine Resources in Aquafeeds’, *North American Journal of Aquaculture*, vol. 81, no. 1, pp. 13–39.

Tveterås, S & Tveterås, R 2010, ‘The global competition for wild fish resources between livestock and aquaculture’, *Journal of Agricultural Economics*, vol. 61, no. 2, pp. 381–397.

Tyedmers, PH, Watson, R, & Pauly, D 2005, ‘Fueling Global Fishing Fleets’, *Ambio*, vol. 34, no. 8, pp. 635–638.

United Nations 2014, *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)*.

United Nations 2015a, ‘Transforming our world: The 2030 agenda for sustainable development’, *United Nations General Assembly*, , no. 1, pp. 1–41.

United Nations 2015b, *Department of Economic and Social Affairs, Population Division. World Population Prospect: The 2015 Revision, Key Findings and Advance Tables.*

United Nations 2019, 'UN Comtrade', , p. http://comtrade.un.org/.

United Nations Department of Economic and Social Affairs Population Division. 2019, *World Population Prospects 2019: Highlights (ST/ESA/SER.A/423).*

United Nations Security Council 2016, 'Report of the Secretary General on the situation with respect to piracy and armed robbery at sea off the coast of Somalia', , vol. S/2016/843, no. October, pp. 1–18.

Uppsala Universitet 2017, *ViEWS: a political Violence Early-Warning System*, *Department of peace and conflict research*, <http://www.pcr.uu.se/research/views/>.

USDA 2019, *Revision of Categorical Eligibility in the Supplemental Nutrition Assistance Program (SNAP)*.

Vandergeest, P, Tran, O, & Marschke, M 2017, 'Modern day slavery in Thai fisheries: academic critique, practical action', *Critical Asian Studies*, vol. 49, no. 3, pp. 461–464.

Veramaris 2019, *Salmon novelty in France: Supermarché Match launches salmon fed with Veramaris' innovative natural marine algal oil*, *Newsroom*, <https://www.veramaris.com/press-releases-detail/salmon-novelty-in-france-supermarche-match-launches-salmon-fed-with-veramaris-innovative-natural-marine-algal-oil.html?utm_source=Kivvit_O&utm_medium=Twitter&utm_campaign=Supermarche_Match_Announcement>.

Vigani, M et al. 2015, 'Food and feed products from micro- algae : Market opportunities and challenges for the EU', *Trends in Food Science and Technology*, vol. 42, pp. 81–92.

Vince, J & Haward, M 2019, 'Hybrid governance in aquaculture : Certification schemes and third party accreditation', *Aquaculture*, vol. 507, pp. 322–328.

Viseu, A 2015, 'Integration of social science into research is crucial', *Nature World View*, vol. 525, p. 291.

Waldron, A et al. 2017, 'Agroforestry Can Enhance Food Security While Meeting Other Sustainable Development Goals', *Tropical Conservation Science*, vol. 20, pp. 1–6.

Wales, WJ & Kolver, ES 2017, 'Challenges of feeding dairy cows in Australia and New Zealand', *Animal Production Science*, vol. 57, no. 7, pp. 1366–1383.

Walk Free Foundation 2018, *The Global Slavery Index (Walk Free Foundation, Perth, 2018).*

Wantchekon, L & Riaz, Z 2019, 'Mobile technology and food access', *World Development*, vol. 117, pp. 344–356.

Warren, R 2011, 'The role of interactions in a world implementing adaptation and mitigation solutions to climate change', *Philosophical Transactions of The Royal Society A*, vol. 369, pp. 217–241.

Watanabe, T 2002, 'Strategies for further development of aquatic fish feeds', *Fisheries Science*, vol. 68 SRC-G, pp. 242–252.

Waterhouse, J et al. 2015, 'Land-sea connectivity, ecohydrology and holistic management of the Great Barrier Reef and its catchments: Time for a change', *Ecohydrology and Hydrobiology*.

Watson, RA et al. 2015, 'Marine foods sourced from farther as their use of global ocean primary production increases', *Nature Communications*, vol. 6, no. May 2014, pp. 1–6.

Watson, RA 2017, ‘A database of global marine commercial, small-scale, illegal and unreported fisheries catch 1950–2014’, *Scientific Data*, vol. 4.

Watson, RA et al. 2017, ‘Global seafood trade flows and developing economies: Insights from linking trade and production’, *Marine Policy*, vol. 82, pp. 41–49.

Weitz, N, Nilsson, M, & Davis, M 2014, ‘A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs’, *SAIS Review of International Affairs*, vol. 34, no. 2, pp. 37–50.

Wheeler, T & von Braun, J 2013, ‘Climate change impacts on global food security.’, *Science.*, vol. 341, no. 6145, pp. 508–13.

White, C & Costello, C 2014, ‘Close the High Seas to Fishing?’, *PLoS Biology*, vol. 12, no. 3, pp. 1–5.

Wijkstrom, U 2009,‘The use of wild fish as aquacultue feed and its effect on income and food for the poor and the undernourished’, in M Hasan & M Halwart (eds.), *Fish as feed inputs for aquaculture: practices, sustainability and implications. Fisheries and Aquaculture Technical Paper*, Rome, pp.371–407.

Willett, W et al. 2019, ‘Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems’, *The Lancet*, vol. 393, no. 10170, pp. 447–492.

Williams, J & Crutzen, PJ 2010, ‘Nitrous oxide from aquaculture’, *Nature Publishing Group*, vol. 3, no. 3, p. 143.

Wiltshire, K, Tanner, J, & Gurgel, C 2015, *Feasibility study for integrated multitrophic aquaculture in southern Australia.*

Winberg, P, Ghosh, D, & Tapsell, L 2009, *Seaweed Culture in Integrated Multi-Trophic Aquaculture —Nutritional Benefits and Systems for Australia.*

Wooldridge, SA & Brodie, JE 2015, 'Environmental triggers for primary outbreaks of crown-of-thorns starfish on the Great Barrier Reef, Australia', *Marine Pollution Bulletin*, vol. 101, no. 2, pp. 805–815.

World Bank 2013, *Fish to 2030 Prospects for Fisheries and Aquaculture*.

Worm, B et al. 2006, 'Impacts of biodiversity loss on ocean ecosystem services', *Science*, vol. 314, no. 5800, pp. 787–790.

Xinhua 2019, 'China launches large-scale salmon farming in Yellow Sea', *XinhuaNet*, p. http://www.xinhuanet.com/english/2019-02/26/c_1378.

Ye, Y et al. 2017, 'FAO's statistic data and sustainability of fisheries and aquaculture_ Comments on Pauly and Zeller (2017)', *Marine Policy*, vol. 81, no. February, pp. 401–405, <http://dx.doi.org/10.1016/j.marpol.2017.03.012>.

Zhou, S, Smith, ADM, & Knudsen, EE 2015, 'Ending overfishing while catching more fish', *Fish and Fisheries*, vol. 16, no. 4, pp. 716–722.

Appendices

Appendix A – Chapter 2 Supplementary Information

Review Methods

We conducted the review of interactions between aquatic and terrestrial food sectors in two phases. The first phase employed a systematic approach where we combined primary and secondary terms detailed in Table S1 to search the title, keywords and abstracts of relevant literature using Web of Knowledge, Scopus and Google Scholar databases. All research domain options (i.e. Life Sciences, Health Sciences, Social Sciences etc) were considered from all timespans.

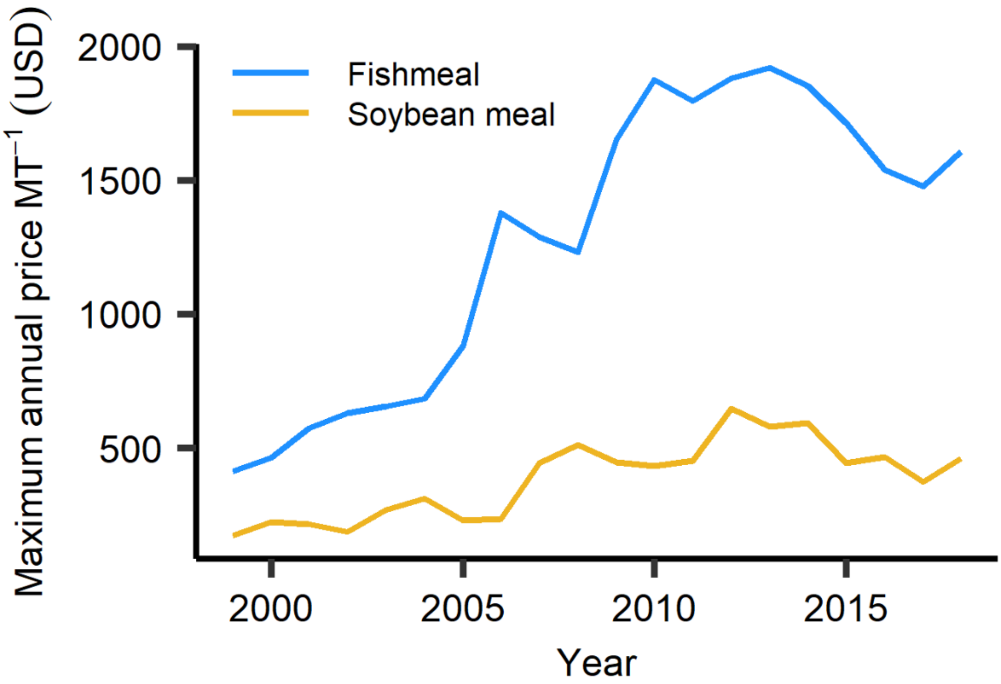
Appendix Table 1 – Systematic search terms used in Web of Knowledge, Scopus, and Google Scholar databases to identify research on food sector interactions.

Primary term (Sector)	**Secondary Term (Search Subject)**	**Relevant novel papers yielded**
“Aquaculture” AND “fisheries” AND (“agriculture” OR “farming”)	“Link” OR “connection” OR “connectivity” OR “interaction” OR “interdependence” OR “interrelation”	56
	OR	
	“Food production” OR “food security”	35
“Aquaculture” AND “fisheries”	“Link” OR “connection” OR “connectivity” OR “interaction” OR “interdependence” OR “interrelation”	81
	OR	
	“Food production” OR “food security”	42

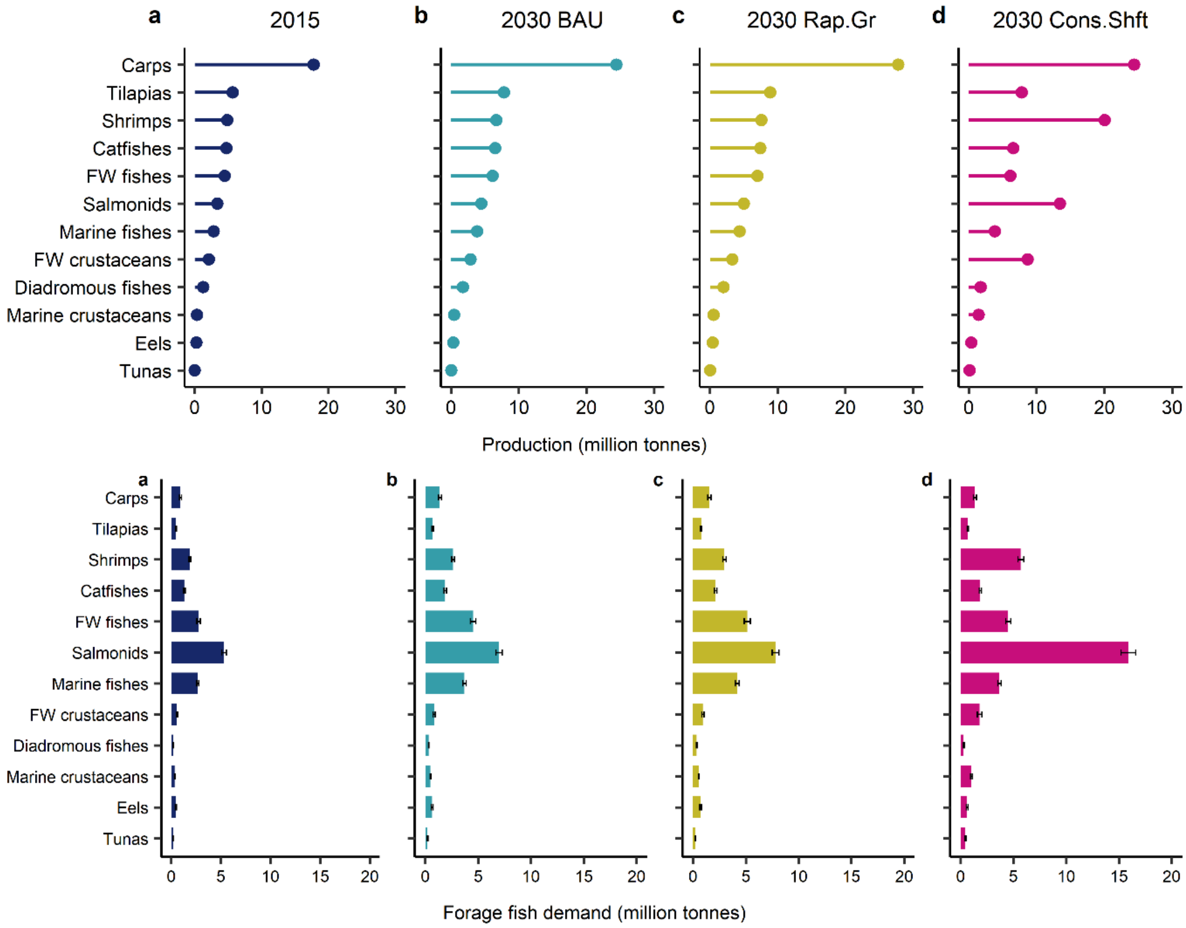
"Aquaculture" AND ("agriculture" OR "farming")	"Link" OR "connection" OR "connectivity" OR "interaction" OR "interdependence" OR "interrelation"	88
	OR	
	"Food production" OR "food security"	3
"Fisheries" AND ("agriculture" OR "farming")	"Link" OR "connection" OR "connectivity" OR "interaction" OR "interdependence" OR "interrelation"	40
	OR	
	"Food production" OR "food security"	0
	Total	**341**

Search results in Scopus and Web of Knowledge produced a mean of 887 documents (no limit provided by Google Scholar searches). Therefore, we sorted search results by relevance to search terms and considered the first 1000 documents listed for inclusion where possible. Three hundred and forty-one papers met our search criteria, but only research articles, reviews, book chapters and reports discussing interactions between terrestrial and aquatic food sectors were included. The second phase of the review expanded the scope of the systematic process by identifying further relevant papers cited by documents found in the systematic search. We defined the categories outlined in Figure 2 qualitatively through aggregating articles describing similar mechanisms of connection between land and sea.

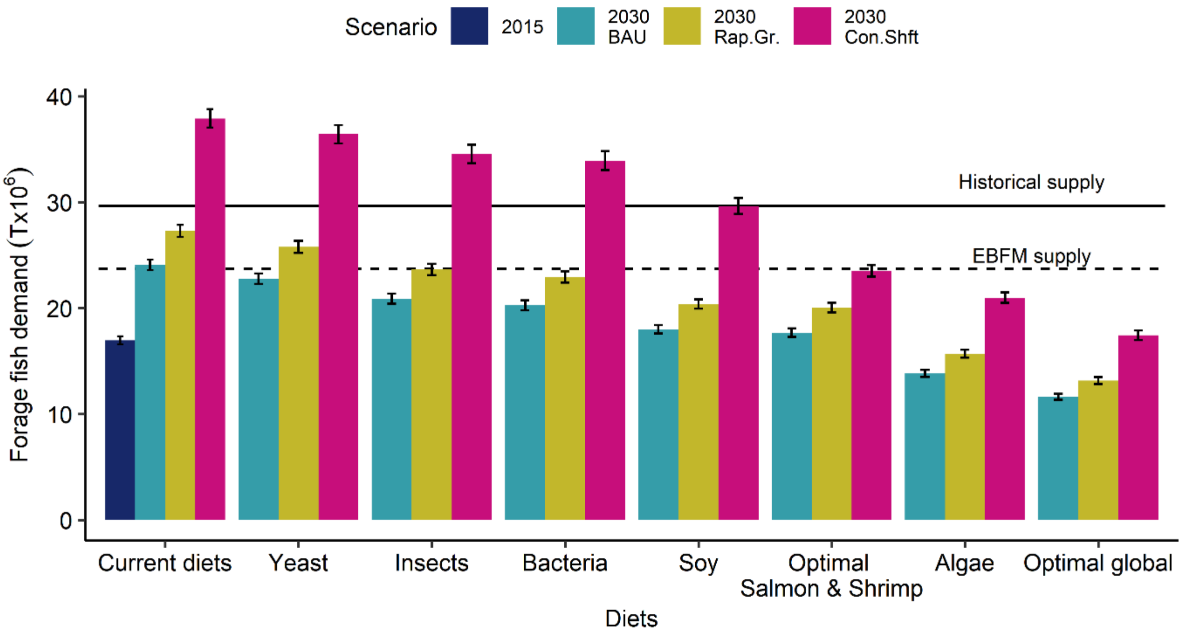
Appendix B – Chapter 3 Supplementary Information



Appendix Figure 1 – Nominal price changes in fishmeal and soybean meal ingredients. Data taken from (Index Mundi 2019)**.**



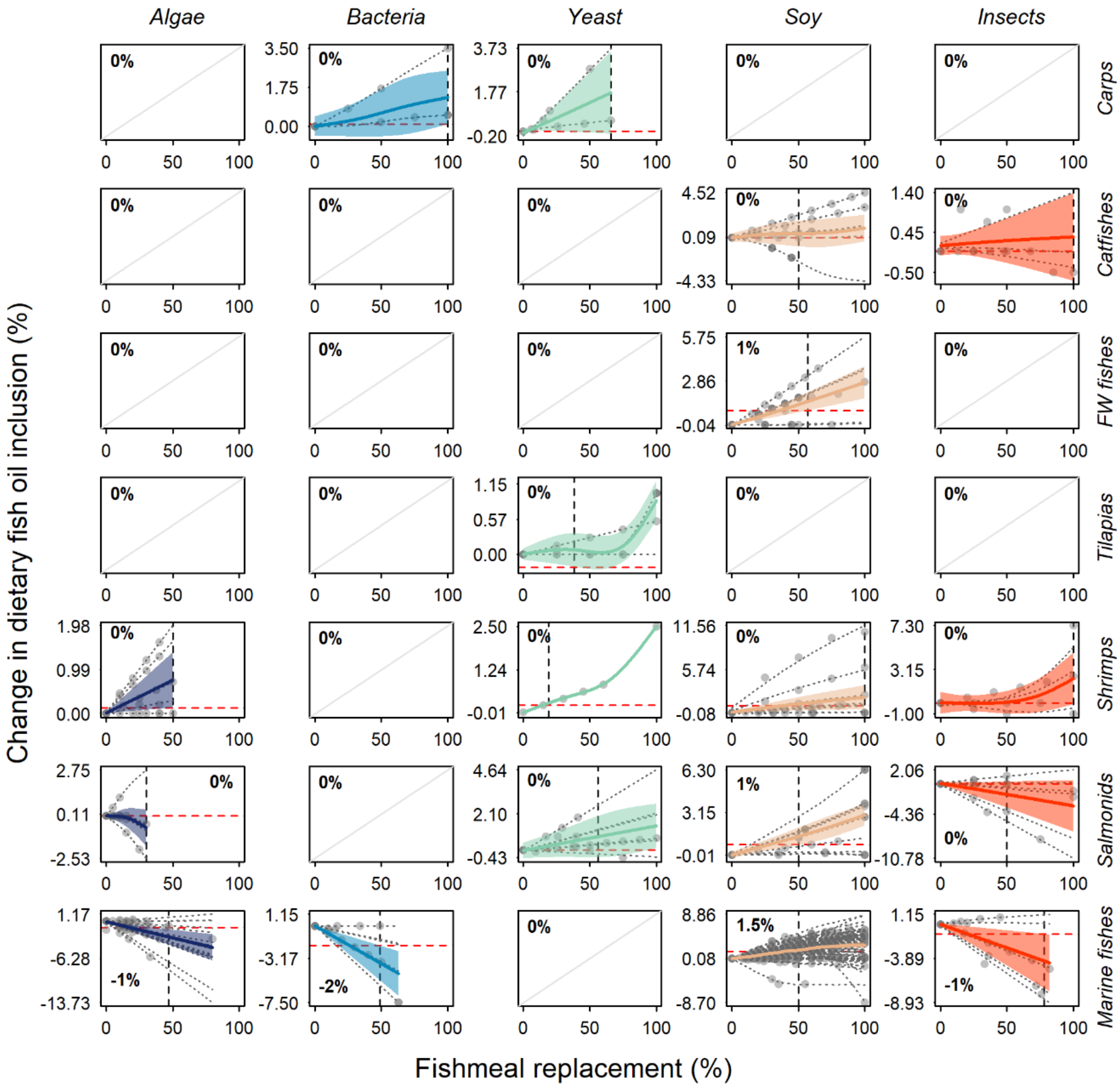
Appendix Figure 2 –Production biomass and forage fish demand by farmed aquatic taxa for current (2015) and 2030 scenarios. Error bars for represent standard deviation of forage fish demand from 500 simulation runs. Colours correspond to scenarios listed at the top.



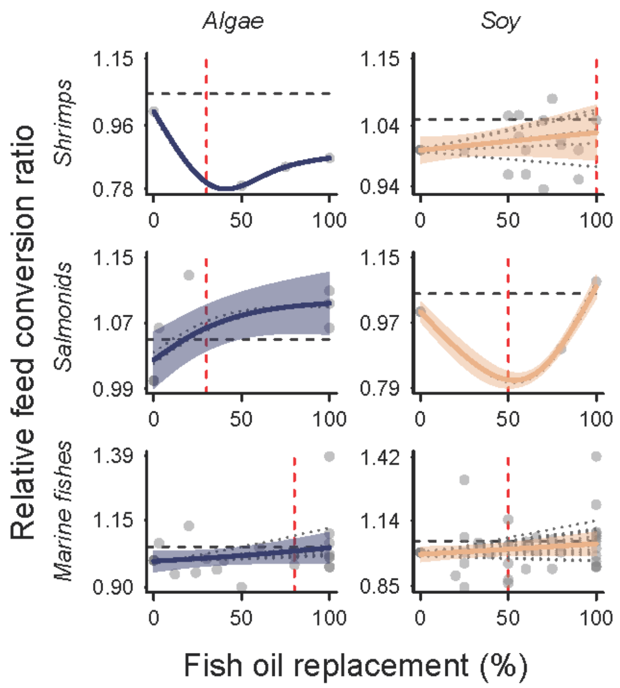
Appendix Figure 3 – Simulated forage fish demand using current diets or novel feeds for 2015 and across 2030 scenarios. Error bars represent standard deviation and solid and dashed lines correspond to historical and EBFM supply limits outlined in Figure 9.

Appendix Table 2 – Median effective forage fish replacement thresholds for novel feed types across animal groups and for animal groups across novel feed types

	Median replacement threshold (nearest %)	
	Fishmeal	**Fish oil**
Ingredients		
Algae	55	100
Bacteria	85	-
Yeast	60	-
Soy	50	30
Insects	100	-
Animal Group		
Carps	100	-
Catfishes	75	-
Freshwater fishes	32.5	-
Tilapias	70	-
Shrimps	85	65
Salmonids	52.5	32.5
Marine fishes	75	100



Appendix Figure 4 – Change in dietary fish oil inclusion with fishmeal replacement. Solid coloured lines represent mean response from mixed-effect smoother model and confidence bands represent 95% confidence intervals. Different colours distinguish feed types. Black vertical dashed lines represent optimal fishmeal replacement levels identified in Figure 10. Red horizontal dashed lines illustrate change in dietary fish oil associated with fishmeal replacement threshold. Plots with diagonal grey lines indicate insufficient or no data for modelling purposes identified from systematic review process.



Appendix Figure 5 – Change in relative feed conversion ratio with fish oil replacement. Solid coloured lines and shading represent fitted mixed-effects model mean response and 95% confidence intervals respectively. Different colours distinguish feed types. Vertical dashed lines indicate the optimal thresholds for fishmeal replacement for each taxon. Note feed conversion ratios here were either not clearly different to zero or were at their optimum (lowest) at the point of optimal fishmeal replacement.

Appendix Table 3 – Summary of fishmeal and oil replacement thresholds without change to feed conversion or n3:n6 fatty acid ratios. For each replacement threshold identified for fishmeal or oil, the change in the opposing marine ingredient is indicated. Note that for studies where fish oil replacement is indicated, we assume this replacement level is feasible with the levels of fishmeal replacement indicated (i.e. fish oil replacement feasibility is prioritized over the change in dietary fish oil in our calculations).

Taxa	Feed ingredients	Optimal fishmeal replacement (%)	Change in dietary fish oil (%)	Optimal fish oil replacement (%)	Change in dietary fishmeal (%)
Carps	Algae	100	0	n/a	n/a
	Bacteria	100	0	n/a	n/a
	Yeast	65	0	n/a	n/a
	Soy	35	0	n/a	n/a
	Insects	100	0	n/a	n/a
Catfishes	Algae	10	0	n/a	n/a
	Bacteria	0	0	n/a	n/a
	Yeast	100	0	n/a	n/a
	Soy	50	0	n/a	n/a
	Insects	100	0	n/a	n/a

Taxa	Feed ingredients	Optimal fishmeal replacement (%)	Change in dietary fish oil (%)	Optimal fish oil replacement (%)	Change in dietary fishmeal (%)
FW fishes	Algae	0	0	n/a	n/a
	Bacteria	10	0	n/a	n/a
	Yeast	0	0	n/a	n/a
	Soy	55	1	n/a	n/a
	Insects	0	0	n/a	n/a
Tilapias	Algae	60	0	n/a	n/a
	Bacteria	100	0	n/a	n/a
	Yeast	40	0	n/a	n/a
	Soy	70	0	n/a	n/a
	Insects	95	0	n/a	n/a
Shrimps	Algae	50	0	100	0
	Bacteria	85	0	n/a	n/a
	Yeast	20	0	n/a	n/a
	Soy	100	0	30	0
	Insects	100	0	n/a	n/a
Salmonids	Algae	30	0	55	0

Taxa	Feed ingredients	Optimal fishmeal replacement (%)	Change in dietary fish oil (%)	Optimal fish oil replacement (%)	Change in dietary fishmeal (%)
	Bacteria	0	0	n/a	n/a
	Yeast	55	0	n/a	n/a
	Soy	50	1	10	0
	Insects	100	0	n/a	n/a
Marine fishes	Algae	80	-1	100	0
	Bacteria	10	-2	n/a	n/a
	Yeast	75	0	n/a	n/a
	Soy	50	1.5	100	0
	Insects	80	-1	n/a	n/a

Appendix Table 4 – Feed conversion ratios, dietary forage fish inclusion and feeding practice parameters for forage fish demand simulations(Froehlich, Jacobsen, et al. 2018, Tacon & Metian 2008, Tacon & Metian 2015). Ranges randomly sampled 500 times from a uniform distribution. All 2030 scenarios assumed the maximum of the range of proportion that are fed. Note salmons, smelts, and trouts were disaggregated during demand simulations due to slight dietary differences but aggregated to salmonids for analysis.

Taxa	Feed conversion ratio	Dietary fishmeal inclusion (%)	Dietary fish oil inclusion (%)	Proportion fed (%)
Carps	1.1-1.6	1-2	0	55-65
Catfishes	1.1-1.7	2-3	1-1.4	80-85
FW fishes	1.1-1.7	15-25	2-3	40-60
Tilapias	1.1-1.6	1-2	0	90-100
Shrimps	1.1-1.6	5-8	1-2	85-90
Marine crustaceans	1.1-1.6	8-16	3-4	97-100
FW crustaceans	1.1-1.8	5-10	0.8-1	55-60
Diadromous fishes	1.1-1.7	2-2.5	1	50-60
Salmons and Smelts	1.1-1.3	8-12	6-8	100
Trouts	1.1-1.3	8-12	4-6	100
Marine fishes	1.1-1.6	8-16	3-4	97-100
Eels	1.1-1.5	25-25	2-3	97-100
Tunas	4.6-7.4	8-16	3-4	100

Appendix Table 5 –Search terms applied to databases to identify, screen and extract experimental data on forage fish replacement in aquaculture feeds by algae, bacteria, yeast, soy or insect ingredients.

		SEARCH TERMS
INGREDIENT	**Algae**	(algae OR micro-algae OR microalgae OR cladophora OR chlorella OR scenedesmus OR schizochytrium OR haematococcus OR nanofrustulum OR tetraselmis OR poryphora OR isocrysis OR ulva)
		OR
	Bacteria	(bacteria OR bacterial OR single cell protein OR single-cell protein OR microbe OR microbial OR spirulina OR arthrospira)
		OR
	Yeast	(yeast OR distiller's OR distiller OR brewer's OR brewer OR baker's OR baker)
		OR
	Soy	(soy OR soybean OR soya OR soyabean)
	Insect	(insect OR insects OR larvae OR pupae OR grub OR fly OR housefly OR silkworm OR mealworm OR worm OR grasshopper OR Chironomid OR Chironomidae)
		AND
		(Replacement)
		AND
FISHMEAL OR FISH OIL		(fishmeal OR fish meal) O*R* (fish oil)
		AND
ANIMAL GROUPS		(carp OR salmon OR trout OR shrimp OR prawn OR tilapia OR catfish OR crab OR lobster OR grouper OR snapper OR seabream OR flounder OR turbot OR seabass OR cod OR meagre OR amberjack OR eel OR barramundi OR milkfish OR snakehead OR perch OR drum OR tuna)
FILTERS	Fields	TITLE OR ABSTRACT OR KEYWORDS
	Category	ALL

	Year	2008 – 2018

Appendix C – Chapter 4 Supplementary Information

Supplementary Notes

The size of a shock seemed dependent on both where it occurs and its driver. Intuitively, the largest shocks tended to occur in regions where large-scale production exists, such as East Asia and Europe, with shocks in Oceania smaller on average (Appendix Figure 5). However, the largest shocks across all sectors were driven, at least in part, by geopolitical crises. For example in our analysis, the largest shock to crop production occurred in Nigeria during outbreaks of violent conflict in 2009 where unsafe working conditions disrupted farmers' access to land, fertilisers, herbicides and seeds (Appendix Figure 5a). In the livestock sector, the largest shock occurred in Mexico in 1989 after successive economic crises exacerbated by drought[1] (Appendix Figure 5b). Whereas the largest fisheries (USSR) and aquaculture (North Korea) shocks happened during the fall of communism in Europe, as production subsidies, export markets, and consumer demand fell away with the dissolution of the Council for Mutual Economic Assistance[2–4] (Appendix Figure 5c,d). The indirect effects of such geopolitical events reinforce how shocks can propagate through interconnected trade networks.

There was no consistent relationship between size of shocks and their recovery time (Appendix Figure 5). The longest recovery times across all sectors represent step changes in production where no recovery occurred before the time-series end. For crop production, recovery was longer on average in East Asia where flooding was the driver for almost all shocks (Appendix Figure 5a). For livestock, fisheries and aquaculture, recovery was longest on average in Europe and Central Asia, largely because of shocks associated with the Soviet Union collapse or overfishing in wild stocks (Appendix Figure 5b,c,d**).**

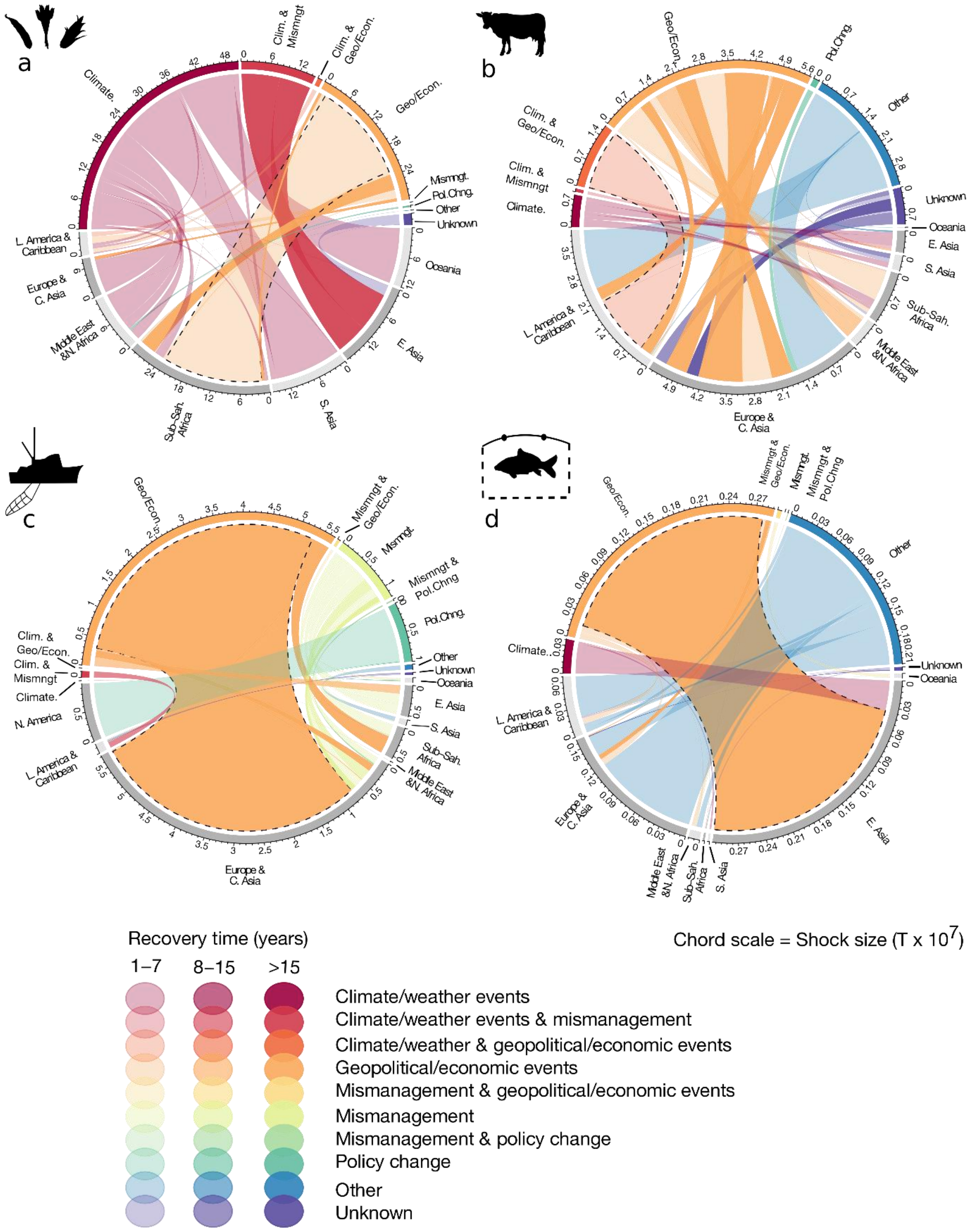
Supplementary Methods

The sensitivity of the detection method outlined in Methods depends on the values for a number of parameters used including LOESS model span, Cook's distance threshold, duration of the production baseline, and the average type used (i.e. mean or median). This becomes particularly important when looking at temporal trends in shock frequency and understanding how sensitive these trends are to changes in each parameter.

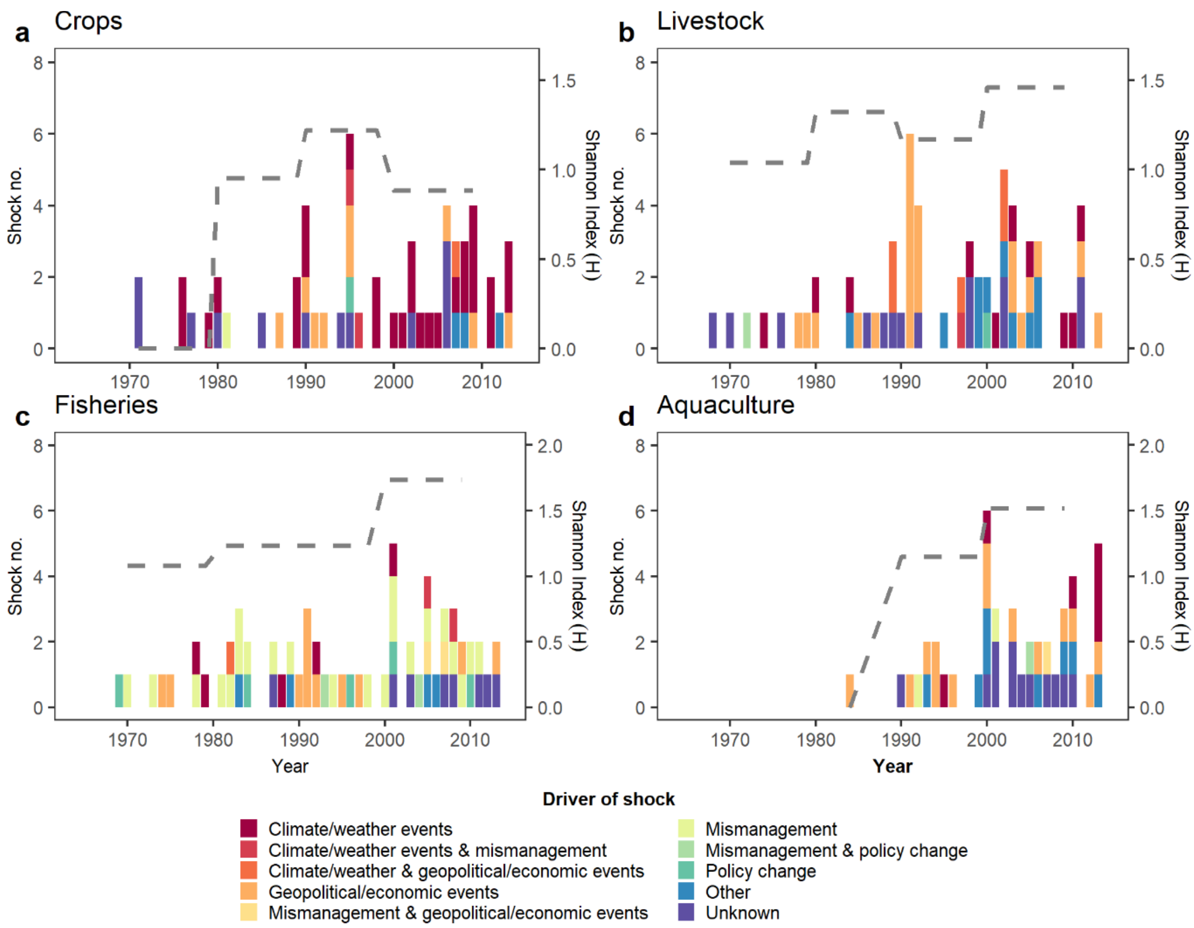
To establish a reasonable combination of parameters that allow us to account for uncertainty in shock detection, particularly in temporal analyses, we constructed a confidence interval of shock frequencies over time. We ran the shock detection analysis using a range of values for LOESS span (0.2 – 0.8, by 0.1), duration used for production baseline average (3, 5, 7, and 9 years) and average type (mean or median). The minimum and maximum of annual shock frequencies produced by changing these parameters yielded a plausible range of shock frequencies over time (Appendix Figure 7). To select the combination to apply to our analysis of shock size, frequency, recovery times, and drivers, we identified the combination that minimised the sum of squared residuals with the median of this range through time. This combination was a LOESS span of 0.6, and 7-year median production baseline (Appendix Figure 7).

To determine a Cook's distance value to use for identifying outliers in all analyses, we tested the number of shocks detected against incremental changes to Cook's distance values between two very different rules of thumb (1 and 4/(n-k-1)). The value of 0.3 is the point in this relationship, reasonable across all sectors, where the number of shocks detected begins to asymptote (Appendix Figure 9). This is very similar to the value used by Gephart et al [3] and is robust to changes in LOESS model span, baseline duration and average type (Appendix Figure 9). Note we conducted sensitivity analysis of Cook's distance values separately as we wanted to optimise sensitivity within practical bounds for this study rather than simply selecting a central value.

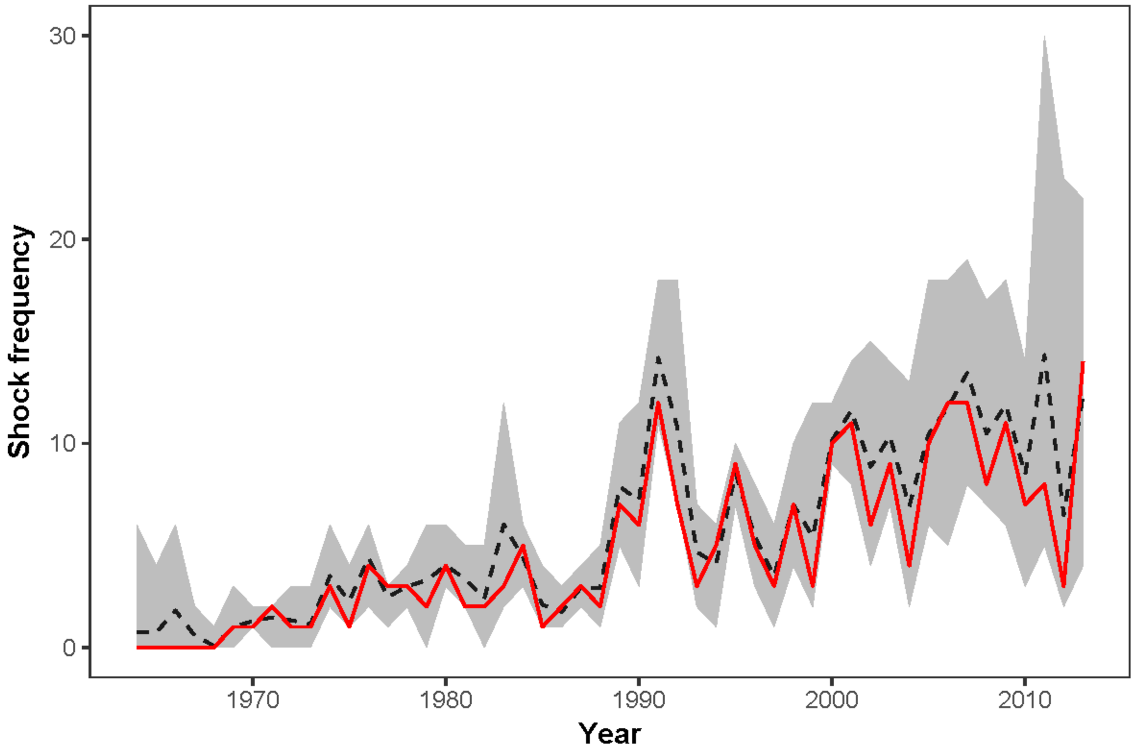
Supplementary Figures



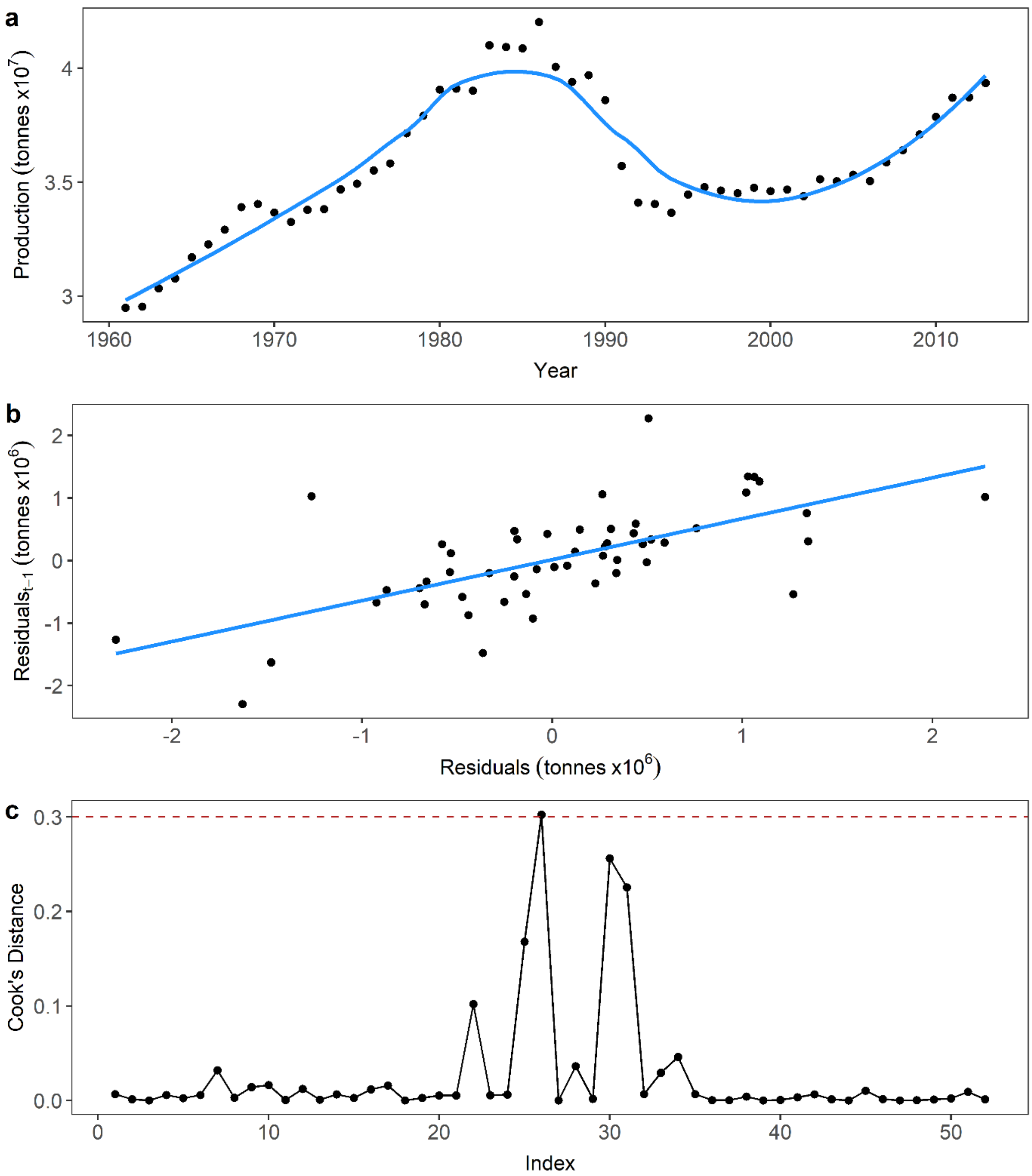
Appendix Figure 6 – Shock size, recovery time and drivers across geographical regions for crop (a), livestock (b), fisheries (c) and aquaculture (d) sectors. Each shock represented by a chord flowing from a driver to a region. Shock sizes indicated by width of the chord (tonnes x10^7), recovery times indicated by chord transparency, and chord colour indicates driver type. Dashed lines lines highlight the biggest shock detected for each sector.



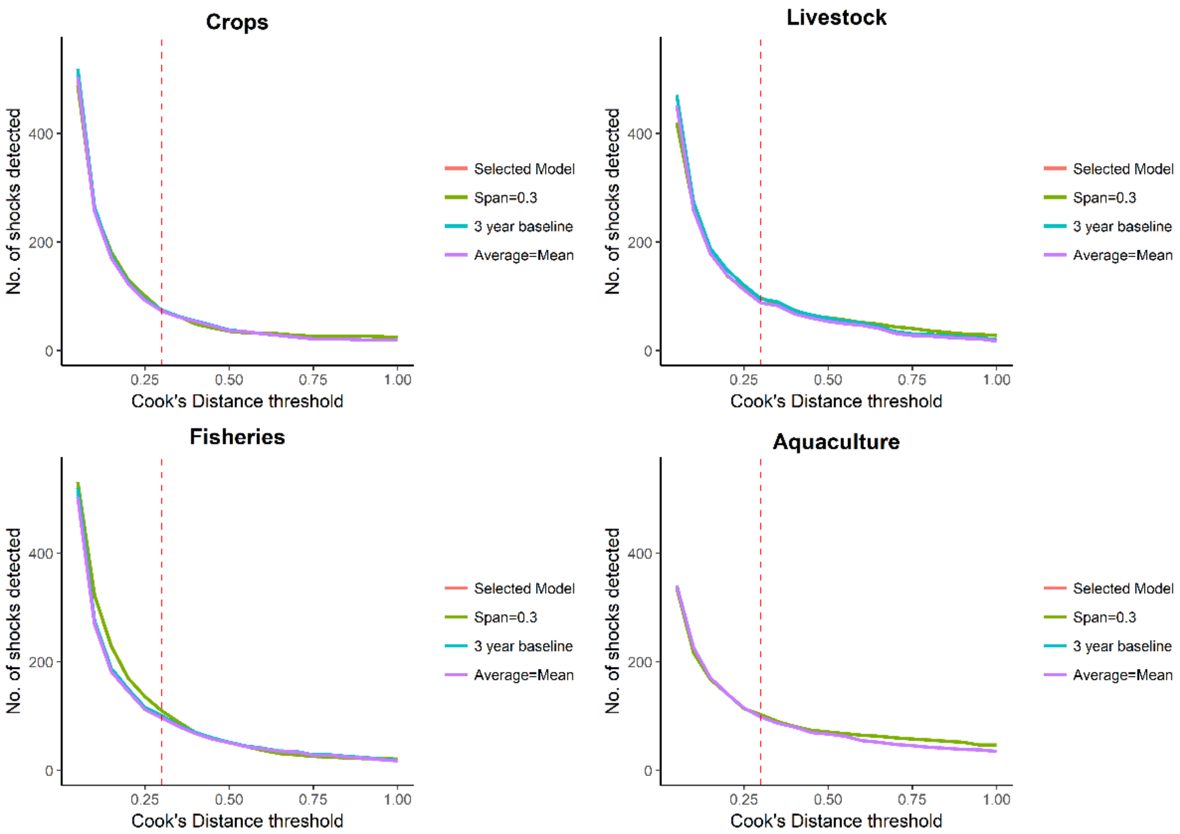
Appendix Figure 7 – Temporal trends in shock drivers across a) crop b) livestock c) fisheries d) aquaculture. Dashed grey line indicates the decadal diversity of drivers with shocks of an unknown driver omitted.



Appendix Figure 8 – Shock frequency through time summed across all sectors for a range of parameter combinations. Light grey confidence interval represents range of plausible shock frequencies dependent on span, baseline and average type used in shock detection. Dashed black line is mean of the confidence interval frequencies. Solid red line represents parameter combination that minimizes the sum of squared residuals with the confidence interval mean (parameters selected for this analysis).



Appendix Figure 9 - Statistical shock detection method. a. Local polynomial regression (LOESS) model fitted to food production time-series **b.** Regression of model residuals against lag-1 residuals **c.** Production shock in 1988 identified as outlier from regression in b using Cook's Distance measures



Appendix Figure 10– Comparisons of number of shocks detected in crop, livestock, fisheries and aquaculture time series with incremental changes to Cook's distance values. Lines represent either the combination of model parameters used in this study ('Selected Model', LOESS span = 0.6, production baseline = 7 years and average type used = median), or repeated with changes to model span, production baseline or average type. Vertical dashed line represents the Cook's distance value of 0.3 used in this study

Appendix Table 6 – Identified causes for production shocks across all sectors. Asterisks indicate possible drivers for shocks of an unknown cause based on events occurring in country at the shock point. We highlight shocks that did not recover by the end of the time series (2013) by NR adjacent to the number of years between the shock point and 2013.

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Afghanistan	2001	1146371	1	Severe droughts from 1999-2001	5	Climate/weather events	Meterological	South Asia	South Asia	Yes
Crops	Albania	1992	700580	16	Transition to market-based economy in early 1990s	6	Geopolitical/economic events	Economic	EuCA	Southern Europe	Yes
Crops	Antigua and Barbuda	1995	471	1	Reduction in crop output associated with damage from Hurricane Luis	7	Climate/weather events	Meterological	LACa	Caribbean	No
Crops	Australia	2007	12018352	1	Annual rainfall in 2006 40-60% below normal over most of the country, in part caused by the 2006/07 El Niño event	8,9	Climate/weather events	Meterological	Oceania	Australia/NZ	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Bahrain	1981	30551	32NR	Urban expansion and salinization of ground water led to significant losses in agricultural areas	10	Mismanagement	Other	MENA	Western Asia	No
Crops	Bermuda	1971	1017	14	Oil price fluctuations in the US economy from 1969-1972*	11	Unknown	Unknown	North America	North America	No
Crops	Bhutan	2000	135694	4	Heavy seasonal monsoon rainfall and flash floods across the country	12,13	Climate/weather events	Meterological	South Asia	South Asia	No
Crops	Burundi	2012	87394	1	Dramatic decrease in banana production between 2007 and 2012 due to the effects of Xanthomonas wilt	14	Other	Disease	SSA	East Africa	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Cameroon	1987	367152	1	Severe economic crisis due to decline in world prices of oil, coffee and cocoa resulted in shrinking agricultural investment	15,16	Geopolitical/economic events	Economic	SSA	Central Africa	No
Crops	Cayman Islands	2004	240	9NR	Hurricane Ivan caused damage across agricultural sector of over US $5.6 millions	17	Climate/weather events	Meterological	LACa	Caribbean	No
Crops	Chile	2007	986109	1	Rising world food prices combined with severe winter frosts in Chile reduced yields for vegetables, pulses and some fruits	18	Climate/weather & geopolitical/economic events	Mixed	LACa	South America	No
Crops	Comoros	1985	8250	1	Effects of Cyclone Kamisy on Cassava and Yams*		Unknown	Unknown	SSA	East Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Cuba	2006	1469850	7 NR	Restructuring in sugar industry led to systemic declines in agricultural productivity	19	Geopolitical/economic events	Economic	LACa	Caribbean	No
Crops	DPRK	1995	6800710	18 NR	Torrential rainfall causing severe flooding and mudslides affecting up to 16% of agricultural areas	4	Climate/weather events & mismanagement	Meterological	East Asia	East Asia	No
Crops	DPRK	1996	8298824	17 NR	As above with recurrent flooding into 1996.	4	Climate/weather events & mismanagement	Meterological	East Asia	East Asia	No
Crops	Democratic Republic of the Congo	1995	3396734	18 NR	Civil unrest during the 1990s preventing agricultural investment and displacing the rural work force.	20,21	Geopolitical/economic events	Conflict	SSA	Central Africa	Yes
Crops	Dominica	1979	11248	2	Hurricane David effects on banana crop	22	Climate/weather events	Meterological	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Dominican Republic	2008	129906	1	Destruction of plantain crop by Tropical Storm Noel late 2007	23	Climate/weather events	Meterological	LACa	Caribbean	No
Crops	Ecuador	1998	412931	1	Heavy rains causing widespread flooding and crop failures	24,25	Climate/weather events	Meterological	LACa	South America	Yes
Crops	French Polynesia	2006	204	1	Unknown		Unknown	Unknown	Oceania	Polynesia	No
Crops	Gambia	2011	94155	1	Severe drought reducing crop production by over 50% in some crops e.g. Millet	26	Climate/weather events	Meterological	SSA	West Africa	No
Crops	Guadeloupe	1980	96781	2	Hurricane David in 1979 followed by Hurricane Allen in 1980 destroying the banana crop	27	Climate/weather events	Meterological	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Guam	2002	1102	2	Super-typhoon Pongsona causing widespread devastation in Guam accounting for $130 million damage*	28	Unknown	Unknown	Oceania	Micronesia	No
Crops	India	2002	14092939	1	Severe drought across major growing regions affecting major kharif crops	29	Climate/weather events	Meterological	South Asia	South Asia	No
Crops	Iran (Islamic Republic of)	2008	6510785	1	Drought reducing wheat production by 34%	30	Climate/weather events	Meterological	MENA	South Asia	No
Crops	Iraq	2009	2134230	1	Drought 2009 -10 in major wheat growing areas	31	Climate/weather events	Meterological	MENA	Western Asia	Yes
Crops	Kiribati	1989	2800	1	Drought and effect largely on coconut plantations	32	Climate/weather events	Meterological	Oceania	Micronesia	No
Crops	Liberia	1995	136526	1	Liberian Civil War	33	Geopolitical/economic events	Conflict	SSA	West Africa	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Libya	1971	10307	1	Dip in productivity after 1969 coup d'etat*		Unknown	Unknown	MENA	North Africa	No
Crops	Libya	1977	60112	1	Libya-Egypt War*		Unknown	Unknown	MENA	North Africa	No
Crops	Madagascar	2013	484817	2	Drought causes large crop and depletion of seed stores	34	Climate/weather events	Meterological	SSA	East Africa	Yes
Crops	Malawi	2005	1600136	1	Drought reduced staple harvest to only 37% of requirements	35	Climate/weather events	Meterological	SSA	East Africa	No
Crops	Maldives	1990	16743	23 NR	Unknown		Unknown	Unknown	South Asia	South Asia	No
Crops	Mali	2013	484899	2	Northern Mali Conflict displacing over 300 000 people and disrupting crop production	36	Geopolitical/economic events	Conflict	SSA	West Africa	Yes
Crops	Namibia	1998	16707	1	Severe drought affecting 25000 people and	28,37	Climate/weather events	Meterological	SSA	Southern Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					abandonment of farms						
Crops	Nauru	2007	272	6 NR	Significant decline in coconut crop due to hispid beetles infestations	38	Other	Pest	Oceania	Micronesia	No
Crops	Nauru	2008	234	5 NR	Significant decline of coconuts due to hispid beetles infestations	38	Other	Pest	Oceania	Micronesia	No
Crops	Nigeria	2009	21555081	1	Iinternal conflict throughout Nigeria reducing agricultural output	36	Geopolitical/economic events	Conflict	SSA	West Africa	Yes
Crops	Niue	1990	1217	6	Banana, breadfruit, papaya and taro crops devastated by Cyclone Ofa	39	Climate/weather events	Meterological	Oceania	Polynesia	No
Crops	Norway	1976	288148	1	Precipitation deficit evident in late winter of 1975 and	40	Climate/weather events	Meterological	EuCA	Northern Europe	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					drought into 1976						
Crops	Pakistan	2002	199835	1	Drought from 1999 through 2002 caused 70% reduction in wheat among other crops	41	Climate/weather events	Meterological	South Asia	South Asia	Yes
Crops	Paraguay	2009	485042	1	Severe drought required immediate relief for agricultural livelihoods	42	Climate/weather events	Meterological	LACa	South America	No
Crops	Peru	1990	846197	1	Lack of investment and structural changes in agriculture in the early 1990s through recession	43	Geopolitical/economic events	Economic	LACa	South America	No
Crops	Republic of Korea	1980	2202191	1	Unknown		Unknown	Unknown	East Asia	East Asia	Yes
Crops	Saint Kitts and Nevis	1990	598	1	Hurrican Hugo caused major damage to	44	Climate/weather events	Meterological	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					crops, particularly sugar towards end of 1989						
Crops	Saudi Arabia	1995	371562	9	Economic pressure forced a reduction in subsidies for wheat and barley growing	45	Policy change	Economic	MENA	Western Asia	No
Crops	Somalia	1991	673387	22 NR	Civil war displaced over a million people and decimated agricultural production	46	Geopolitical/economic events	Conflict	SSA	East Africa	Yes
Crops	Syrian Arab Republic	1989	2443833	1	Drought affecting wheat crop	47	Climate/weather events	Meterological	MENA	Western Asia	No
Crops	Timor-Leste	2011	96394	2	Disrupted planting for 2011 due to severe La Nina flooding in 2010	48	Climate/weather events	Meterological	East Asia	SE Asia	No
Crops	Togo	2013	117639	2	Drought reducing harvest and planting of soy and rice	49	Climate/weather events	Meterological	SSA	West Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Crops	Tokelau	1994	101	10	Unknown		Unknown	Unknown	Oceania	Polynesia	No
Crops	Tokelau	2006	8	2	Unknown		Unknown	Unknown	Oceania	Polynesia	No
Crops	United Kingdom	1976	7054926	1	Major drought - lowest rainfall in the UK in over 200 years resulting 20-30% drops in potato, oilseed and wheat	50	Climate/weather events	Meterological	EuCA	Northern Europe	No
Crops	United Republic of Tanzania	2003	624231	1	Drought in northern and central Tanzania affecting 2 million people. 85% of sorghum, maize and groundnuts affected	51	Climate/weather events	Meterological	SSA	East Africa	No
Crops	Vanuatu	1995	3273	1	Unknown		Unknown	Unknown	Oceania	Melanesia	No
Crops	Venezuela (Bolivarian Republic of)	2009	306179	2	Drought in 2009 due to El Nino event, 70-80% of Venzeuelan rice and	52,53	Climate/weather events	Meterological	LACa	South America	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					maize affected						
Crops	Wallis and Futuna Islands	2006	2009	7	Unknown		Unknown	Unknown	Oceania	Polynesia	No
Livestock	Angola	2006	18307	1	Outbreaks of haematic and symptomatic carbuncle, nodular bovine dermatitis and contagious peripneumonia causing cattle losses	54	Other	Disease	SSA	Central Africa	No
Livestock	Antigua and Barbuda	1992	299	2	Unknown		Unknown	Unknown	LACa	Caribbean	No
Livestock	Argentina	2003	1616044	2	Foot and Mouth Disease outbreak in 2000 leading to further declines until 2003	55	Other	Disease	LACa	South America	No
Livestock	Austria	1988	328632	11	Unknown		Unknown	Unknown	EuCA	Western Europe	Yes
Livestock	Bangladesh	1980	153425	4	Drought over 7 major growing	56	Climate/weather events	Meterological	South Asia	South Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					regions in 1980						
Livestock	Barbados	1992	3194	4	Downturn in productivity following economic recession. Agricultural output declined between 1991 and 1994 due to poorly performing export sectors - largely due to the 1990 oil price shock	57	Geopolitical/economic events	Economic	LACa	Caribbean	Yes
Livestock	Belize	1989	5239	3	Unknown		Unknown	Unknown	LACa	Central America	No
Livestock	Bhutan	2009	4342	4 NR	Agricultural damage from flash floods from cyclone Aila influenced 12 of 20 districts in Bhutan	58,59	Climate/weather events	Meterological	South Asia	South Asia	No
Livestock	British Virgin Islands	1968	80	8	Unknown		Unknown	Unknown	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Bulgaria	1991	599963	22 NR	Dissolution of Council for Mutual Economic Assistance (COMECON) resulted in trade disruption for Bulgarian livestock. Production output dropped nearly 15% from 1988 to 1991. By 1993 cattle inventories were down 40% and poultry 53% from 1988 levels	60	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Livestock	Cabo Verde	2011	12901	2 NR	Unknown		Unknown	Unknown	SSA	West Africa	No
Livestock	Comoros	2002	473	1	Unknown		Unknown	Unknown	SSA	East Africa	No
Livestock	Côte d'Ivoire	1998	26453	6	Unknown		Unknown	Unknown	SSA	West Africa	No
Livestock	Cuba	1991	337699	22 NR	Loss of subsidized petroleum, fertilizer subsides and export markets from USSR dissolution Gross	61	Geopolitical/economic events	Economic	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					agricultural output declined by 40%						
Livestock	DPRK	1992	49880	9	Cessation of subsidised coal and oil from USSR following demise and subsequent withdrawal of aid from China. Further declines in 1994 after China withdrew.	4	Geopolitical/economic events	Economic	East Asia	East Asia	No
Livestock	DPRK	1997	85561	2	Food production continued to dip until 1997 following floods 1995-96.	4,62	Climate/weather events & mismanagement	Meterological	East Asia	East Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Dominica	2005	1191	2	Productivity decline during 2000s across the agriculture sector due to rural-urban migration in younger demographic	63	Geopolitical/economic events	Demographic	LACa	Caribbean	No
Livestock	Dominican Republic	2003	53821	1	Financial crisis from 2003-2004*	64	Geopolitical/economic events	Unknown	LACa	Caribbean	No
Livestock	Fiji	1984	14788	2	Brucellosis outbreak in dairy industry	65	Other	Disease	Oceania	Melanesia	No
Livestock	Finland	1970	325600	43 NR	Unknown		Unknown	Unknown	EuCA	Northern Europe	No
Livestock	Former Czechoslovakia	1991	1214615	22 NR	Velvet Revolution and transition to market-based economy	66	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Livestock	French Polynesia	1999	169	12	Reduced milk production with Leptospirosis event	67	Other	Disease	Oceania	Polynesia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Germany	1987	802351	1	Decentralisation of agricultural production following the demise of COMECON and reunification with West Germany	2	Geopolitical/economic events	Economic	EuCA	Western Europe	No
Livestock	Greenland	1972	166	7	Collapse of reindeers herds either a result of mass starvation over winter or possibly issues with data reporting/ management between years	68	Mismanagement & policy change	Mixed	North America	North America	No
Livestock	Grenada	1979	554	34 NR	Crash of dairy production during and following national coup and political restructuring	69	Geopolitical/economic events	Mixed	LACa	Caribbean	Yes
Livestock	Guadeloupe	1990	3340	23 NR	Unknown		Unknown	Unknown	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Guam	1989	301	24 NR	Abandonment of agricultural livelihoods in the late 1980s - number of farmers across Guam crashed in 1987 after Cyclone Lynn	70	Climate/weather & geopolitical/economic events	Mixed	Oceania	Micronesia	No
Livestock	Hungary	1991	576871	22 NR	Dissolution of COMECON reduced inputs and markets for export and competition from western European countries led to a massive decline in agricultural productivity	71	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Livestock	Indonesia	1998	242122	3	Drought driven by El Nino combined with Asian economic crisis	72	Climate/weather events	Mixed	East Asia	SE Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Iraq	1991	334354	9	Sanctions on Iraq during first Gulf War led to complete cut-off of imported feed grains. Domestic feed grain supply also decreased as it was redirected to human food.	73	Geopolitical/economic events	Economic	MENA	Western Asia	No
Livestock	Iraq	2003	267805	10 NR	Invasion of Iraq during second gulf war	73	Geopolitical/economic events	Conflict	MENA	Western Asia	No
Livestock	Kuwait	1991	89451	3	First Gulf War and Invasion of Kuwait by Iraq	74	Geopolitical/economic events	Conflict	MENA	Western Asia	Yes
Livestock	Libya	1985	6575	1	Investment withdrawn from agriculture with economic durntrun from oil crisis	75	Geopolitical/economic events	Economic	MENA	North Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Malawi	2002	16665	2	Malawi food crisis induced by floods in 2001 and complacency of projected food production. IMF encouraged sale (and so depletion of grain stores). Rush to sell livestock for staples leading to flooded market and a crash in livestock prices. Collapse of many rural livelihoods even migration to neighbouring Zambia.	76	Climate/weather & geopolitical/economic events	Mixed	SSA	East Africa	No
Livestock	Maldives	2005	200	8 NR	2004 Tsunami	77	Other	Geological	South Asia	South Asia	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Mali	2011	15783	1	Northern Mali Conflict displacing over 300 000 people and disrupting agriculture	36,78	Geopolitical/economic events	Conflict	SSA	West Africa	Yes
Livestock	Mali	2013	89793	1 NR	Northern Mali Conflict displacing over 300 000 people and disrupting agriculture	36,78	Geopolitical/economic events	Conflict	SSA	West Africa	Yes
Livestock	Mauritania	1974	70845	4	Drought from 1968 - 1972 causes large losses to pastoralists as herd numbers dwindle to 1.5 million head	79	Climate/weather events	Meterological	SSA	West Africa	No
Livestock	Mauritius	1978	5593	11	Severe economic crisis hindering agriculture and trade of agricultural goods	80	Geopolitical/economic events	Economic	SSA	East Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Mexico	1989	1627163	2	Successive droughts and economic crises from 1986-1989	1	Climate/weather & geopolitical/economic events	Mixed	LACa	Central America	No
Livestock	Mongolia	2001	50505	3	20 Million head of livestock perished in two mass mortality events (dzuds) in between 2000-2002 and 2009-2010. Dzuds driven by a combination of summer droughts, heavy snowfall, high winds, and extremely low winter temperatures	81	Climate/weather events	Meterological	East Asia	East Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Mongolia	2010	83518	1	20 Million head of livestock perished in two mass mortality events (dzuds) in between 2000-2002 and 2009-2010. Dzuds driven by a combination of summer droughts, heavy snowfall, high winds, and extremely low winter temperatures	81	Climate/weather events	Meterological	East Asia	East Asia	No
Livestock	Montserrat	2006	665	7 NR	Economic downturn induced by infrastructure damage from the eruption of Soufriere volcano in 2005	82,83	Other	Geological	LACa	Caribbean	No
Livestock	Nauru	1976	2	2	Unknown		Unknown	Unknown	Oceania	Micronesia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Nicaragua	1980	299828	19	Nicaraguan civil war causing loss of production facilities or dangerous conditions inhibiting producers livelihoods. Large production losses across the country totalling USD $ 4.3 million in 1981	84	Geopolitical/economic events	Conflict	LACa	Central America	No
Livestock	Niger	1984	52170	6	Drought reduced feed crops and fodder yielding insufficient grazing or feed for cattle in the second half of 1984	85	Climate/weather events	Meterological	SSA	West Africa	No
Livestock	Nigeria	2011	162689	1	Significant floods in southern Nigeria causing livestock losses	86	Climate/weather events	Meterological	SSA	West Africa	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Norway	2000	162861	13 NR	Subsidy system reform incentivising fewer small farms and more large scale farms causing a restructure within Norwegian agriculture	87	Policy change	Economic	EuCA	Northern Europe	No
Livestock	Paraguay	2000	38383	2	Foot and mouth outbreak in 2000	88	Other	Disease	LACa	South America	No
Livestock	Saint Kitts and Nevis	2006	228	7 NR	Combination of agricultural theft, insufficient grazing lands left many livestock rearers unwilling to sell livestock in 2005 onwards	89	Geopolitical/economic events	Mixed	LACa	Caribbean	No
Livestock	St. Vincent and the Grenadines	2003	368	4	Tropical storm Lili significantly impacting agriculture sector	90	Climate/weather events	Meterological	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	St. Vincent and the Grenadines	2005	487	2	Significant livestock losses from Hurricane Emily	91	Climate/weather events	Meterological	LACa	Caribbean	No
Livestock	Sao Tome	1974	131	39 NR	Widespread disruption with a shift in political regime during Carnation Revolution*	92	Unknown	Unknown	SSA	Central Africa	No
Livestock	Seychelles	2002	821	11 NR	Unknown		Unknown	Unknown	SSA	East Africa	No
Livestock	Singapore	1999	44411	14 NR	National abattoir closure following detection of Nipah Virus	93	Other	Disease	East Asia	SE Asia	No
Livestock	Somalia	1992	739565	4	Famine caused by conflict exacerbating a water crisis. Livestock targeted by militia during civil war to use hunger as a weapon	94	Geopolitical/economic events	Mixed	SSA	East Africa	Yes
Livestock	Sri Lanka	1986	98183	4	Unknown		Unknown	Unknown	South Asia	South Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Sri Lanka	1998	132611	14	Severe drought*		Unknown	Unknown	South Asia	South Asia	No
Livestock	Timor-Leste	1997	469	1	Combined influence of severe El-Nino drought and Asian financial crisis led to soaring fed prices from imports	95	Climate/weather & geopolitical/economic events	Mixed	East Asia	SE Asia	No
Livestock	Turkey	2002	1545816	1	Outbreak of foot and mouth disease	96	Other	Disease	EuCA	Western Asia	No
Livestock	Venezuela (Bolivarian Republic of)	2004	69910	1	Protests and conflict over proposed land reform and shutdown of the oil industry major economic disturbances for agriculture	97	Geopolitical/economic events	Mixed	LACa	South America	Yes
Livestock	Zambia	1995	6962	3	Food and mouth disease outbreak and widespread infection in 1995	98	Other	Disease	SSA	East Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Livestock	Zimbabwe	2003	29439	1	Drought causes food crisis and disturbances across dairy farms caused milk production to decline sharply	99	Climate/weather & geopolitical/economic events	Mixed	SSA	East Africa	No
Fisheries	Afghanistan	2001	450	12 NR	Severe droughts (1999-2001) impacting inland fisheries	5100	Climate/weather events	Meterological	South Asia	South Asia	Yes
Fisheries	Albania	1991	9165.578	22 NR	Fall of communism in Eastern Europe	101	Geopolitical/economic events	Economic	EuCA	Southern Europe	Yes
Fisheries	Angola	1975	315545.3	38	Independence from Portugal, withdrawal of Portuguese fleet from domestic operations	102	Geopolitical/economic events	Economic	SSA	Central Africa	No
Fisheries	Anguilla	2010	40.7581	1	Overfishing of nearshore waters	103	Mismanagement	Overfishing	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Fisheries	Antigua and Barbuda	1981	1511.095	1	Overfishing in lobster fishery, reporting change also likely as FAO data only accepted in mid 1980s	104	Mismanagement	Overfishing	LACa	Caribbean	No
Fisheries	Barbados	1989	1325.079	3	1989 identified as a year of particularly low natural productivity followed and preceeded by years of high productivity	105	Other	Other	LACa	Caribbean	Yes
Fisheries	Belgium	1969	3102.253	2	Drop off in capacity after government subsidies issued between 1961 -1969	106	Policy change	Economic	EuCA	Western Europe	No
Fisheries	Belize	2003	10022.06	4	Beginning of a decline in catch per unit effort	107	Mismanagement	Overfishing	LACa	Central America	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Fisheries	Botswana	1978	200	2	Severe drought from 1978-1979 – Botswanan inland fisheries sensitive to environmental fluctuations	108–110	Climate/weather events	Meterological	SSA	Southern Africa	No
Fisheries	Bulgaria	1978	16351.84	2	Overfishing and eutrophication in the black sea during the 1970s resulting in dramatic decline of small pelagics	111112	Mismanagement	Mixed	EuCA	Eastern Europe	No
Fisheries	Burundi	1997	698	16 NR	Closure to landing sites on Lake Tangyanika in 1996 due to civil unrest	113	Geopolitical/economic events	Conflict	SSA	East Africa	No
Fisheries	Central African Republic	2013	2000	1 NR	Political turmoil reducing fish supply by 40% due threat violence along countries	114	Geopolitical/economic events	Conflict	SSA	Central Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					rivers and the loss of fishing equipment						
Fisheries	China, Macao SAR	1987	4897.452	26 NR	Declining resource in polluted nearshore waters and inefficient fleet	115	Mismanagement	Pollution	East Asia	East Asia	No
Fisheries	Cook Islands	2013	368.5621	1 NR	Unknown		Unknown	Unknown	Oceania	Polynesia	No
Fisheries	Dominica	1983	214.9291	10	Overfishing of nearshore species by mid 1980s	116	Mismanagement	Overfishing	LACa	Caribbean	No
Fisheries	Fiji, Republic of	1994	3442.686	1	Overfishing of sea cucumber stocks	117	Mismanagement	Overfishing	Oceania	Melanesia	No
Fisheries	Former USSR	1992	4947742	21 NR	Breakup of Soviet Union leading to reduced capacity and overfished stocks	3	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Fisheries	Germany	1973	98731.97	40 NR	Collapse of mackerel stocks in North Sea in early 1970s	118	Mismanagement	Overfishing	EuCA	Western Europe	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					due to overfishing						
Fisheries	Greece	1998	78556.77	4	Overfishing leading to general decline in total landings from the mid-1990s	119	Mismanagement	Overfishing	EuCA	Southern Europe	No
Fisheries	Greece	2001	75954.02	1	Overfishing leading to general decline in total landings from the mid-1990s	119	Mismanagement	Overfishing	EuCA	Southern Europe	No
Fisheries	Grenada	1982	469.5915	1	Political instability in Grenada disrupted tourism-based fisheries combined with damage from Hurricane Allen	120	Climate/weather & geopolitical/economic events	Mixed	LACa	Caribbean	Yes
Fisheries	Guinea	2008	7556.994	1	Unknown		Unknown	Unknown	SSA	West Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Fisheries	Hungary	1991	10492	22 NR	Transition to market economy with significant impact on seafood production	121	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Fisheries	Italy	2005	195668.5	8 NR	Overfishing since WWII in the Adriatic region	122	Mismanagement	Overfishing	EuCA	Southern Europe	No
Fisheries	Jamaica	2001	5129.559	12 NR	Closure in conch fishery in 2000, reopened in 2001 at lower quota than pre 2000	123124	Policy change	Management	LACa	Caribbean	No
Fisheries	Kenya	2001	22446.6	10	Intense overfishing on kenyan coral reefs and in Lake Victoria	125126	Mismanagement	Overfishing	SSA	East Africa	No
Fisheries	Kiribati	2000	14797.08	4	Overfishing of mullet	127	Mismanagement	Overfishing	Oceania	Micronesia	No
Fisheries	DPRK	1983	184107.9	4	High catch fluctuation in EEZ before closure of distant fleet due to oil crisis	128	Mismanagement	Overfishing	East Asia	East Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					suggest overfishing						
Fisheries	Kuwait	1991	7080.867	1	Majority of Kuwait's fishing fleet removed during Iraq Invasion	129	Geopolitical/economic events	Conflict	MENA	Western Asia	Yes
Fisheries	Lesotho	2001	6	1	Unknown driver to carp production decline		Unknown	Unknown	SSA	Southern Africa	No
Fisheries	Liberia	1995	4335.824	4	Liberian civil war	130	Geopolitical/economic events	Conflict	SSA	West Africa	Yes
Fisheries	Malaysia	2006	1635.816	1 NR	Tsunami damage to vessels and gear on the western Peninsula coast	131	Other	Geological	East Asia	SE Asia	No
Fisheries	Maldives	2007	15707.75	6 NR	Overfishing of tuna stocks, increased Somali piracy in productive regions and recent increases in fuel prices	132	Mismanagement & geopolitical/economic events	Mixed	South Asia	South Asia	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Fisheries	Mayotte	2004	803.2232	9 NR	Shift away from pirogue fishing in the lagoon due to decreasing catches	133	Mismanagement & policy change	Mixed	SSA	Caribbean	No
Fisheries	Montserrat	1988	56.39493	3 NR	Damage from Hurricane Hugo	134	Climate/weather events	Meterological	LACa	Caribbean	No
Fisheries	Montserrat	1992	103.7283	21 NR	Damage from Hurricane Hugo	134	Climate/weather events	Meterological	LACa	Caribbean	No
Fisheries	Netherlands Antilles	2011	18723.66	2 NR	Unknown		Unknown	Unknown	LACa	Caribbean	No
Fisheries	New Caledonia	1983	2209.096	1	Large fluctuation in sea cucumber fishery, natural productivity pulse	135	Other	Other	Oceania	Melanesia	No
Fisheries	New Zealand	1996	5509.09	1 NR	Reduced TAC on many fish stocks	136	Policy change	Management	Oceania	Australia/NZ	No
Fisheries	Niue	2009	9.39722	4 NR	Stock decline reducing subsistence landings and a closure of fish	137	Geopolitical/economic events	Mixed	Oceania	Polynesia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					processing plant in 2008						
Fisheries	Palau	1984	8151.412	23 NR	Closure of the bait fish fishery in 1982	138	Policy change	Management	Oceania	Micronesia	No
Fisheries	Philippines	2011	174619.7	2 NR	Overexploitation edpleting marine resources	139	Mismanagement	Overfishing	East Asia	SE Asia	Yes
Fisheries	Romania	1990	133690	23 NR	Dissolution of USSR and overfishing during soviet era	140	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Fisheries	Saint Lucia	1979	1904.803	5	Decimation of landings (particularly urchins) by Hurricane David in 1979 followed by destruction of fishing boats by Hurricane Allen in 1980	141142	Climate/weather events	Meterological	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Fisheries	Saint Vincent/Grenadines	2003	12010.91	10 NR	Unknown		Unknown	Unknown	LACa	Caribbean	No
Fisheries	Samoa	1984	6229.257	1	Overfishing of groundfish causing decline by mid 1980s coupled with a drop in tuna catch	143	Mismanagement	Overfishing	Oceania	Polynesia	No
Fisheries	Seychelles	2007	15808.66	2	Steep drop in tuna catches following abnormally high years suggest previous overexploitation	144	Mismanagement	Overfishing	SSA	East Africa	No
Fisheries	Solomon Islands	2005	39404.7	1	Dramatic decreases in sea cucumber fishery thought due to domestic tensions and resource depletion	145	Mismanagement & geopolitical/economic events	Mixed	Oceania	Melanesia	No
Fisheries	South Africa	1970	151399.7	3	Sardine crash following overfishing	146	Mismanagement	Overfishing	SSA	Southern Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Fisheries	Sri Lanka	2005	80016.1	1	Tsunami caused extensive fishing gear and infrastructure damage	147	Other	Geological	South Asia	South Asia	No
Fisheries	St Helena	2012	198.3568	1 NR	Unknown		Unknown	Unknown	SSA	Central Africa	No
Fisheries	St. Pierre and Miquelon	1993	25072.44	20 NR	Cod Moratorium in Atlantic	3	Mismanagement & policy change	Management	EuCA	North America	No
Fisheries	Suriname	2009	4956.326	1	Overfishing across multiple taxa combined with very high discard rates	148	Mismanagement	Overfishing	LACa	South America	No
Fisheries	Switzerland	1982	1383	31 NR	Overfishing, pollution, water extraction from inland waters a number of possible causes	149	Mismanagement	Mixed	EuCA	Western Europe	No
Fisheries	Syrian Arab Republic	2008	1825.426	5 NR	Shock to inland fisheries during severe drought in Syria combined with	150	Climate/weather events & mismanagement	Mixed	MENA	Western Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					overfishing by artisanal operations at sea						
Fisheries	Tanzania, United Rep. of	2008	23206.06	1	Overfishing evident in years leading up to 2008	151	Mismanagement	Overfishing	SSA	East Africa	No
Fisheries	Turkey	1989	122755.2	4	Collapse of fishery in Black Sea due to overcapacity and pollution	152	Mismanagement	Mixed	EuCA	Western Asia	No
Fisheries	Turks and Caicos Is.	1987	1466.889	1	Unknown		Unknown	Unknown	LACa	Caribbean	No
Fisheries	United States of America	2010	978894.5	1	Quota enforcement to prevent collapse	153	Policy change	Management	North America	North America	No
Fisheries	US Virgin Islands	2007	342.983	6 NR	Unknown		Unknown	Unknown	LACa	Caribbean	No
Fisheries	Venezuela, Boliv Rep of	2005	106956	8 NR	Collapse of sardine fishery due to shift in plankton community combined with over exploitation	154155	Climate/weather events & mismanagement	Mixed	LACa	South America	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					in upwelling zone						
Fisheries	Viet Nam	1974	158669.1	9	Displaced of Vietnamese fishing fleet during the end of Vietnamese war efforts	156	Geopolitical/economic events	Conflict	East Asia	SE Asia	No
Aquaculture	Albania	1991	1306	15	Demise of financial support from the USSR	157	Geopolitical/economic events	Economic	EuCA	Southern Europe	Yes
Aquaculture	Austria	1990	874	23 NR	Unknown		Unknown	Unknown	EuCA	Western Europe	Yes
Aquaculture	Bahrain	2001	0.5	1	Unknown		Unknown	Unknown	MENA	Western Asia	No
Aquaculture	Burundi	2010	32.7	1	Unknown		Unknown	Unknown	SSA	East Africa	Yes
Aquaculture	Congo	1994	70	5	Down turn in aquaculture production from prolonged internal conflict from 1993-2000	158	Geopolitical/economic events	Conflict	SSA	Central Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Aquaculture	Congo	2000	74	13 NR	Down turn in aquaculture production from prolonged internal conflict from 1993-2000	158	Geopolitical/economic events	Conflict	SSA	Central Africa	No
Aquaculture	Congo, Dem. Rep. of the	1996	100	1	Declining productivity after cessation of US, Belgian and French cooperation projects in 1990	159	Geopolitical/economic events	Economic	SSA	Central Africa	Yes
Aquaculture	Dominica	2010	8	3 NR	Severe drought in 2009/2010 posing challenges for both crops and production in inland water ways combined with economic downturn in wake of the GFC	160	Climate/weather events	Mixed	LACa	Caribbean	No
Aquaculture	Ecuador	2000	47569	4	White spot syndrome in Shrimp Industry causing	161	Other	Disease	LACa	South America	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					huge drop in production						
Aquaculture	El Salvador	2013	539	1 NR	Huge drop in freshwater fish production (largely Nile Tilapia) during severe drought across region 2013-2014. Agricultural sector widely affected	162163	Climate/weather events	Meterological	LACa	Central America	No
Aquaculture	Faroe Islands	2006	23970	2	Infectious salmon anaemia outbreaks 2000-2005	164	Other	Disease	EuCA	Northern Europe	No
Aquaculture	French Guiana	1992	63	21 NR	Reduction in larval population from mangroves used for stocking in brown shrimp culture	165	Mismanagement	Other	LACa	South America	No
Aquaculture	Guadeloupe	2005	9.639	8 NR	Unknown		Unknown	Unknown	LACa	Caribbean	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Aquaculture	Guam	2003	60.5	10 NR	Super-typhoon Pongsona causing widespread devastation in Guam accounting for $130 million damage*	28	Unknown	Unknown	Oceania	Micronesia	No
Aquaculture	Guyana	2008	316	5 NR	Unknown		Unknown	Unknown	LACa	South America	No
Aquaculture	Guyana	2009	97.04	4 NR	Unknown		Unknown	Unknown	LACa	South America	No
Aquaculture	Hungary	1984	5477	29 NR	Transition from centralized to market-driven economy	121	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Aquaculture	Iraq	2013	3881	1 NR	Iraqi insurgency and ensuing conflict destroying boats, equipment and fish ponds	166	Geopolitical/economic events	Conflict	MENA	Western Asia	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Aquaculture	Jamaica	2003	581	1	Severe flooding in 2002 with inland systems prone to damage from fish farm flooding and infrastructure damage*		Unknown	Unknown	LACa	Caribbean	No
Aquaculture	Jordan	2004	28	1	Unknown		Unknown	Unknown	MENA	Western Asia	No
Aquaculture	Kiribati	2007	4825	5	Poor on-farm management and warm waters cited as unfavourable conditions for seaweed but high freight costs and poor currency exchanges rates contributing factors	167	Mismanagement & geopolitical/economic events	Mixed	Oceania	Micronesia	No
Aquaculture	DPRK	1994	262961	19 NR	Withdrawal of Chinese subsidised imports in 1994	4	Geopolitical/economic events	Economic	East Asia	East Asia	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Aquaculture	Madagascar	2009	580.5	1	Expensive shrimp products unable to compete in export markets against cheaper alternatives from EU and political crisis causing economic hardship and farm closures.	168169	Geopolitical/economic events	Economic	SSA	East Africa	Yes
Aquaculture	Mali	2012	21	1	Violent conflict disrupting fishing and aquaculture operations	36	Geopolitical/economic events	Conflict	SSA	West Africa	Yes
Aquaculture	Malta	2005	817	1	Capture-based culture of Bluefin Tuna - overfishing of Bluefin reported by International Commission for the Conservation of Atlantic Tunas leading to implementati	170	Mismanagement & policy change	Mixed	MENA	Southern Europe	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					on of strict quotas						
Aquaculture	Martinique	1995	10	8	Financial crisis in Martinique	171	Climate/weather events	Economic	LACa	Caribbean	No
Aquaculture	Mexico	2010	6794	1	Recurrent vibriosis outbreaks in shrimp production in western Mexico since 2005	163172	Geopolitical/economic events	Disease	LACa	Central America	No
Aquaculture	Morocco	2000	183	5	Declining competitiveness in foreign markets as fish prices decrease but Morocco is still dependent on expensive European feed producrs	173	Geopolitical/economic events	Economic	MENA	North Africa	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Aquaculture	Morocco	2006	728	7 NR	Declining competitiveness in foreign markets as fish prices decrease but Morocco is still dependent on expensive European feed producrs	173	Geopolitical/economic events	Economic	MENA	North Africa	No
Aquaculture	Pakistan	2000	2179	1	Severe drought and pollution slowing production in early 2000s	174	Climate/weather events	Meterological	South Asia	South Asia	Yes
Aquaculture	Palau	2012	0.105	2	Typhoon Yolanda/ Haiyan*		Climate/weather events	Unknown	Oceania	Micronesia	No
Aquaculture	Panama	1999	2778.5	4	White spot disease in shrimp farming	175	Other	Disease	LACa	Central America	No
Aquaculture	Panama	2000	3326.5	3	White spot disease in shrimp farming	175	Other	Disease	LACa	Central America	No
Aquaculture	Philippines	2013	34312.1	2	Super Typhoon Yolanda/ Haiyan	176	Climate/weather events	Meterological	East Asia	SE Asia	Yes

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
Aquaculture	Poland	1993	7342	2	Transition to market economy from centralized system	177	Geopolitical/economic events	Economic	EuCA	Eastern Europe	No
Aquaculture	Saint Lucia	2000	10	1	Large fluctuations likely a function of embryonic stages of algae farming development *		Unknown	Unknown	LACa	Caribbean	No
Aquaculture	Saudi Arabia	2013	6810	1 NR	White spot disease in shrimp farming	178	Other	Disease	MENA	Western Asia	No
Aquaculture	Singapore	2007	524	6	Unknown		Unknown	Unknown	East Asia	SE Asia	No
Aquaculture	South Africa	2001	1318	1	Unknown		Unknown	Unknown	SSA	Southern Africa	No
Aquaculture	Spain	1993	121296	4	Harmful algal blooms	179	Other	HAB	EuCA	Southern Europe	No
Aquaculture	Trinidad and Tobago	2003	6	1	Significant slowdown in agricultural sector during political uncertainty	180	Geopolitical/economic events	Economic	LACa	Caribbean	No
Aquaculture	Uruguay	2001	8.5	2	Low brood stock in key	181	Mismanagement	Other	LACa	South America	No

Sector	Country	Year	Shock size (tonnes)	Recovery time (years)	Driver	Reference	Category	SubCategory	Region	SubRegion	Co-occurrence
					nursery waterways						
Aquaculture	Venezuela, Boliv Rep of	2009	3918.6	1	Large declines in shrimp production following the introduction of Taura syndrome virus in 2005/06	163182	Other	Disease	LACa	South America	Yes
Aquaculture	Venezuela, Boliv Rep of	2010	537.27	1	Large declines in shrimp production following the introduction of Taura syndrome virus in 2005/06	163182	Other	Disease	LACa	South America	Yes

Appendix C References

1. Liverman, D. Vulnerability and adaptation to drought in México. *Nat. Resour. J.* **39,** 99–115 (1999).

2. Petrick, M. *Modernizing Russia's cattle and dairy Sectors under WTO conditions: Insights from East Germany*. *Discussion Paper, Leibniz Institute of Agricultural Development in Transition Economic* **150,** (2014).

3. Gephart, J. A., Deutsch, L., Pace, M. L., Troell, M. & Seekell, D. A. Shocks to fish production: Identification, trends, and consequences. *Glob. Environ. Chang.* **42,** 24–32 (2017).

4. Noland, M. Famine and Reform in North Korea. *Asian Econ. Pap.* **3,** 1–40 (2004).

5. FAO. *FAO/WFP Crop and food supply assessment mission to Afghanistan. Global Information and Early Warning Systems on Food and Agriculture World Food Programme*. (2002).

6. FAO. *Nutrition Country Profile - Republic of Albania. Food and Agricultural Organisation of the United Nations, Rome.* (2005).

7. IICA. *Agriculture in Antigua and Barbuda 1991-1995 and beyond. Working Document. Socioeconomic policy and trade programme. Inter-American Institute for Cooperation on Agriculture*. (1997).

8. Australian Bureau of Statistics. Feature article: 2006 Drought. *1301.0 - Year Book Australia, 2008* http://www.abs.gov.au/ausstats/abs@.nsf/a9ca4374ed (2008). Available at:

http://www.abs.gov.au/ausstats/abs@.nsf/a9ca4374ed453c6bca2570dd007ce0a4/ccc8ead2792bc3c7ca2573d200106bde!OpenDocument.

9. Australian Bureau of Meterology. Short-term relief but long-term drought persists. *Reports and Summaries* http://www.bom.gov.au/climate/drought/archive/2007 (2007). Available at: http://www.bom.gov.au/climate/drought/archive/20070604.shtml.

10. FAO. *Bahrain Irrigation in the Middle East region in figures – AQUASTAT Survey 2008*. (2008).

11. Hamilton, J. *Historical Oil Shocks Working Paper 16790. NBER Working Paper Series, National Bureau of Research, Massachusetts*. (2011).

12. OCHA. Bhutan - Floods and Landslides OCHA Situation Report No. 2. *ReliefWeb - United Nations Office for Coordination of Humanitarian Affairs* https://reliefweb.int/report/bhutan/bhutan-floods- (2000).

13. OCHA. India: Floods Appeal No. 19/2000 Situation Report No. 3. International Federation of Red Cross and Red Crescent Studies. *ReliefWeb - United Nations Office for Coordination of Humanitarian Affairs* https://reliefweb.int/report/india/india-floods-ap (2000).

14. Niragira, S. *et al.* Options and Impact of Crop Production Specialization on Small-Scale Farms in the Noth of Burundi. in *4th International conference of the African Association of Agircultural Economists* 1–26 (2013).

15. Fambon, S. *et al.* Slow Progress in Growth and Poverty Reduction in Cameroon. *Growth and Poverty in Sub-Saharan Africa* 293 (2016).

16. Sunderlin, W. D. *et al.* Economic crisis, small-scale agriculture, and forest cover change in southern Cameroon. *Environ. Conserv.* **27,** 284–290 (2000).

17. ECLAC. *The Impact of Hurricane Ivan in the Cayman Islands Part I*. (2004).

18. OECD. *Review of Agricultural Policies: Chile*. (2008). doi:http://dx.doi.org/10.1787/9789264042247-en

19. Mesa-Lago, C. The Cuban Economy in 2006-2007. in *ASCE Association for the Study of the Cuban Economy* (2007).

20. Akitoby, B. & Cinyabuguma, M. Sources of growth in the Democratic Republic of the Congo: a cointegration approach. International Monetary Fund. *IMF Work. Pap.* (2004).

21. FAO. *Special Report: Crop and food supply in Kinshasa and the provinces of Bas-Congo and Bandundu of the Deomcratic Republic of the Congo. FAO Global Information and Early Warning System on Food and Agriculture. Food and Agricultural Organization of the UN, Ro*. (2000).

22. Mohan, P. The economic impact of hurricanes on bananas: A case study of Dominica using synthetic control methods. *Food Policy* **68,** 21–30 (2017).

23. World Bank. *Climate Change Aspects in Agriculture Dominican Republic Country Note.* (2008).

24. Bayer, A. M. *et al.* The 1997–1998 El Niño as an unforgettable phenomenon in northern Peru: a qualitative study. *Disasters* **38,** 351 (2014).

25. OCHA. Ecuador El Niño Floods Situation Report No. 5. *ReliefWeb - United Nations Office for Coordination of Humanitarian Affairs* https://reliefweb.int/report/ecuador/ecuador-el-ni (1998).

26. Yaffa, S. *Loss and damage from drought in the North Bank Region of The Gambia. Loss and Damage in Vulnerable Countries Initiative, case study report. Bonn: United Nations University Institute for Environment and Human Security.* (2013).

27. FAO. *The World Banana Economy, 1970-1984: Structure, Performance, and Prospects. Rome: Food and Agriculture Organization of the United Nations*. (1986).

28. CRED. EM-DAT: The Emergency Events Database. *D. Guha-Sapir,Université catholique de Louvain (UCL)* www.emdat.be (2009). Available at: www.emdat.be. (Accessed: 9th December 2017)

29. Lal, B., Das, H. P., Samui, R. P. & Kashyapi, A. Impact of Drought on Kharif Crops in Southern India during 2002 as Compared with Kharif 2003. *Water Energy Abstr.* **14,** 14–15 (2004).

30. USDA. *USDA Foreign Agricultural Service. Iran: Crop Progress Report. FAS - Office of Global Analysis*. (2009).

31. USDA Foreign Agricultural Service. IRAQ: Drought & Irrigation Shortages Decimate Wheat Harvest in 2009/10. Commodity Intelligence report. United States Department of Agriculture. Accessed at:https://ipad.fas.usda.gov/highlights/2 (2009).

32. Oakes, R., Milan, A. & J, C. Kiribati: CLimate change and migration - Relationships between household vulnerability, human mobility and climate change. Report No. 20. Bonn: United Nations University Institute for Environment and Human Security (UNU-EHS). (2016).

33. FAO WFP. Crop and food supply assessment mission to Liberia Special Report. FAO global Information and Early Warning System on Food and Agriculture World Food Programme. Food and Agricultural Organization of the United Nations. Accessed at: http://www.fao.org/docrep/004/x9208e/ (2000).

34. FAO WFP. Special Report: Crop and Food Security Assessment Mission to Madagascar. http://www.fao.org/docrep/018/aq115e/aq115e.pdf (2013).

35. Makoka, D. *The impact of drought on household vulnerability: The case of rural Malawi. MPRA Paper No. 15399. University of Bonn, Centre for Development Research (ZEF)*. (2008).

36. Kimenyi, M. *et al. The Impact of Conflict and Political Instability on Agricultural Investments in Mali and Nigeria. Afrca Growth Initiative. Working Paper 17.* (2014).

37. Shivute, O. Namibia: Drought crisis looms, Crops wither, farmers abandon cattle posts. *AllAfrica* http://allafrica.com/stories/199803170094.html (1998).

38. FAO. Nauru and FAO Partnering to improve food security and income-earning opportunities. http://www.fao.org/3/a-av263e.pdf (2015).

39. Crocombe, M. *et al.* Polynesia in Review: Issues and Events, 1 July 1989 to 30 June 1990. *Contemp. Pac.* **3,** 191–211 (1991).

40. European Drought Centre. Drought of 1975-1976. Central and Northern Europe. *Major Drought Events* http://www.geo.uio.no/edc/droughtdb/edr/DroughtEve (2013).

41. FAO WFP. Special Report: FAO WFP Crop and food supply assessment mission to Pakistan. http://www.fao.org/docrep/004/Y1260e/Y1260e00.htm (2001).

42. IFRC. *Paraguay Drought DREF operation no. MDRPY007 Glide No. DR-2009-000104-PRY Update no. 1.* (2009).

43. Velazco, J. *Agricultural Production in Peru (1950-1995): Sources of Growth*. (2001).

44. Berke, P. & Wenger, D. *Linking Hurricane Disaster Recovery to Sustainable Development Strategies in Saint Kitts and Nevis, West Indies*. (1991).

45. Elhadj, E. *Camels don't fly, deserts don't bloom: an assessment of Saudi Arabia's experiment in desert agriculture. Occasional Paper No 48 Water Issues Study Group School of Oriental and African Studies (SOAS)/King's College London University of London*. (2004).

46. Jeilani, O. The impact of civil war on crop production in Somalia. in *ICAS VII Seventh International Conference on Agricultural Statistics. Rome* 315–317 (2016). doi:10.1481/icasVII.2016.a06d

47. Al-Khalidi, S. & El Dahan, M. War-ravaged Syria may face worst wheat harvest in 40 years. *Reuters* https://www.reuters.com/article/us-syria-wheat-cro (2014).

48. Tran, P. La Niña blow to crops. *IRIN* http://www.irinnews.org/report/90624/timor-leste-l (2010).

49. OCHA. *2013 Rainy Season Overview West and Central Africa. United Nations Office for Coordination Humanitarian Affairs*. (2013).

50. Wreford, A. & Neil Adger, W. Adaptation in agriculture: Historic effects of heat waves and droughts on UK agriculture. *Int. J. Agric. Sustain.* **8,** 278–289 (2010).

51. OCHA. PWS&D responds to drought in Tanzania. *ReliefWeb - United Nations Office for Coordination of Humanitarian Affairs* https://reliefweb.int/report/united-republic-tanza (2003).

52. Rojas, O., Li, Y. & Cumani, R. *Understanding the drought impact of El Niño on the global agricultural areas: An assessment using FAO's Agricultural Stress Index (ASI)*. (2014).

53. Anon. El Niño intensifies Latin American drought. *The Telegraph* https://www.telegraph.co.uk/expat/expatnews/661392 (2009).

54. Anon. Huila: Over 300,000 Heads Of Cattle Vaccinated. *Agencia Angola Press* http://www.angop.ao/angola/en_us/noticias/economia (2006).

55. Mattion, N. *et al.* Reintroduction of foot-and-mouth disease in Argentina: characterisation of the isolates and development of tools for the control and eradication of the disease. *Vaccine* **22,** 4149–4162 (2004).

56. Keka Israt, A., Matin, I., Rahman, M. & Banu, D. A. Analysis of Drought in Eastern Part of Bangladesh. *20 DAFFODIL Int. Univ. J. Sci. Technol.* **7,** 20–27 (2012).

57. IICA. *Working Paper: Agriculture in Barbados: 1991 -1995 and Beyond*. (1997).

58. UNESCAP. Bhutan Country Presentation. in *Regional Capacity Development Workshop: Mainstreaming DRR in Sustainable Development Planning. United Nations Economic and Social Comission for Asia and the Pacific* http://www.unescap.org/sites/default/files/Bhutan% (2016).

59. Austrian Development Agency. Support to mitigate disaster caused by floods in Bhutan. *Projects* http://www.entwicklung.at/en/projects/detail-en/pr (2009).

60. Schmitz, A., Moulton, K., Buckwell, A. & Davidova, S. *Privatization of agriculture in new market economies: lessons from Bulgaria*. **6,** (Springer Science & Business Media, 2012).

61. Riera, O. & Swinnen, J. Cuba's agricultural transition and food security in a global perspective. *Appl. Econ. Perspect. Policy* **38,** 413–448 (2016).

62. Noland, M., Robinson, S. & Wang, T. Famine in North Korea: Causes and Cures. *Econ. Dev. Cult. Change* **49,** 741–767 (2001).

63. FAO. *Country Report on the State of Plant Genetic Resources for Food and Agriculture: Dominica*. (2008).

64. Anon. Dominican Republic in Crisis. *The New York Times* https://www.nytimes.com/2003/12/29/opinion/dominic (2003).

65. Anon. Cow Disease Hits Fiji. *Solomon Times Online* http://www.solomontimes.com/news/cow-disease-hits- (2009).

66. Chloupkova, J. *Czech Agricultural Sector: Organisational Structure and its Transformation. The Royal Veterinary and Agricultural University. Food and Resource Economic Institute* (2002).

67. Brioudes, A., Warner, J., Hedlefs, R. & Gummow, B. A review of domestic animal diseases within the Pacific Islands region. *Acta Trop.* **132,** 23–38 (2014).

68. Cuyler, C. Success and failure of reindeer herding in Greenland. *Rangifer Rep.* 81–92 (1999).

69. Clegg, P. Revolutionary politics in Grenada - a retrospective. *E-International relations* http://www.e-info/2013/07/02/revolutionary-poli (2013).

70. Bucayu-laurent, C. & Hollyer, J. R. *Some History and Trends of Agriculture on Guam: Data from the U.S. Census of Agriculture and Other Sources, 1920-2007. Agricultural data 01. College of Natural and Applied Sciences. University of Guam.* (2016).

71. Lanzsky, I. & Komives, T. Changing agriculture in Eastern Europe : Hungary as an example. *Agro Food Ind. Hi Tech* 31–33 (1994).

72. FAO. Update on FAO's activities in relation to the 1997/98 El Niño and La Niña. *Newsroom - Food and Agricultural Organisation of the UNited Nations* (1998).

73. Schnepf, R. *CRS Report for Congress. Iraq Agriculture and Food Supply: Background and Issues*. (2004).

74. FAO. *The State of Food and Agriculture. No 25 Food and Agricultural Organisation of the United Nations. Rome*. (2002).

75. Jansen, H. Rangeland development in Northern Libya. *Rangelands* **10,** 178–182 (1988).

76. Devereux, S. The Malawi famine of 2002. *IDS Bull.* **33,** 70–78 (2002).

77. World Bank Asian Development Bank UN. *Maldives Tsunami: Impact and Recovery. Joint Needs Assessment by World Bank-ADB-UN System*. (2004).

78. FAO. *Mali conflict: Contingency and Response Plan. The Sahel Crisis*. (2013).

79. International Bank for Reconstruction and Development. *The Current tconomic Situation And Prospects of Mauritania*. (1974).

80. Gupte, P. Indian Ocean Nation of Mauritius Struggles Through Economic and Political Crisis. *The New York Times* https://www.nytimes.com/1979/11/20/archives/indian (1979).

81. Rao, M. P. *et al.* Dzuds, droughts, and livestock mortality in Mongolia. *Environ. Res. Lett.* **10,** (2015).

82. Pollard, W. & Christ, N. *Caribbean Region: Review of Economic Growth and Development. U . S . International Trade Commission. Investigation Number 332 - 496*. (2008).

83. CARDI. Montserrat: Country Profile. *Carribbean Agricultural Research and Development Institute* http://www.cardi.org/country-offices/montserrate/ (2011).

84. Prévost, G. The" Contra" War in Nicaragua. *J. Confl. Stud.* **7,** (1987).

85. Swinton, S. M. Drought survival tactics of subsistence farmers in Niger. *Hum. Ecol.* **16,** 123–144 (1988).

86. Agbola, B. S., Ajayi, O., Taiwo, O. J. & Wahab, B. W. The August 2011 flood in Ibadan, Nigeria: Anthropogenic causes and consequences. *Int. J. Disaster Risk Sci.* **3,** 207–217 (2012).

87. Forbord, M., Bjørkhaug, H. & Burton, R. J. F. Drivers of change in Norwegian agricultural land control and the emergence of rental farming. *J. Rural Stud.* **33,** 9–19 (2014).

88. Sutmoller, P. & Olascoaga, R. C. The successful control and eradication of Foot-and-mouth disease epidemics in South America in 2001. *Evid. Tempor. Comm. Foot-and-Mouth Dis. Eur. Parliam.* 1–8 (2002).

89. Caribbean Development Bank. St . Kitts and Nevis. *Annu. Econ. Rev.* 91–102 (2005).

90. OCHA. Tropical Storm Lili Situation Report No. 1. *ReliefWeb - United Nations Office for Coordination of Humanitarian Affairs* https://reliefweb.int/report/barbados/tropical-sto (2002).

91. Organisation of Eastern Caribbean States. *Grenada : Macro-Socio-Economic Assessment of the Damage caused by Hurricane Emily*. (2005).

92. Seibert, G. São Tomé and Príncipe 1975-2015: politics and economy in a former plantation colony. *Estud. Ibero-Americanos* **42,** 987 (2016).

93. Paton, N. I. *et al.* Outbreak of Nipah-virus infection among abattoir workers in Singapore. *Lancet* **354,** 1253–1256 (1999).

94. Majid, N. & McDowell, S. Hidden dimensions of the Somalia famine. *Glob. Food Sec.* **1,** 36–42 (2012).

95. OCHA. FAO/WFP crop and food supply assessment mission to Indonesia. *ReliefWeb - United Nations Office for Coordination of Humanitarian Affairs* https://reliefweb.int/report/indonesia/faowfp-crop (1998).

96. Garland, A. J. M. A review of the foot-and-mouth disease situation on Turkey during the last decade, including a critical assessment of past national and international control programmes, and with recommendations for future control. *Rep. 34th Sess. Eur. Comm. Control Foot-and-Mouth Dis. FAO, Rome, Italy. March. Append.* **8,** 80–95 (2001).

97. Wilpert, G. in *Promised Land: Competing Visions of Agrarian Reform* (eds. Rosset, P., Patel, R. & Courville, M.) 249–176 (2006).

98. Chilonda, P. *et al.* Foot and mouth disease in Zambia: a review of the aetiology and epidemiology and recommendations for possible control. *Rev. Sci. Tech. Int. Off. Epizoot.* **18,** 585–592 (1999).

99. FAO WFP. *Special Report: Crop and food supply assessment mission to Zimbabwe*. (2002).

100. FAO. *Fisheries and Aquaculture Country Profiles. The Islamic Republic of Afghanistan*. (2015).

101. Moutopoulos, D., Bradshaw, B. & Pauly, D. Reconstruction of Albania fishery catches by fishing gear. *Fish. Cent. Work. Pap. Ser.* **12,** (2015).

102. Belhabib, D. & Divovich, E. in *Fisheries catch reconstructions: West Africa, Part II. Fisheries Centre Research Reports vol.23(3)* **23,** 115–128 (2015).

103. Ramdeen, R., Zylich, K. & Zeller, D. Reconstruction of Total Marine Fisheries Catches for Anguilla (1950-2010). *Fish. catch Reconstr. Islands, Part IV* **22,** 1–8 (2014).

104. Georges, J., Ramdeen, R., Zylich, K. & Zeller, D. Reconstruction of total marine fisheries catch for Antigua and Barbuda (1950-2010). *Work. Pap. Ser. Fish. Centre, Univ. Br. Columbia* 17 (2015).

105. Mohammed, E., Lindop, A., Parker, C. & Willoughby, S. Reconstructed fisheries catches of Barbados, 1950-2010. *Work. Pap. Ser. Fish. Centre, Univ. Br. Columbia* **86,** 6–9 (2015).

106. Lescrauwaet, A. K., Fockedey, N., Debergh, H., Vincx, M. & Mees, J. Hundred and eighty years of fleet dynamics in the Belgian sea fisheries. *Rev. Fish Biol. Fish.* **23,** 229–243 (2013).

107. Zeller, D., Graham, R. & Harper, S. in *Too Precious to Drill: the Marine Biodiversity of Belize* **19,** 142–151 (2011).

108. Belbase, K. & Morgan, R. Food security and nutrition monitoring for drought relief management: The case of Botswana. *Food Policy* **19,** 285–300 (1994).

109. Masih, I., Maskey, S., Mussá, F. E. F. & Trambauer, P. A review of droughts on the African continent: A geospatial and long-term perspective. *Hydrol. Earth Syst. Sci.* **18,** 3635–3649 (2014).

110. Kolding, J., van Zwieten, P., Marttin, F. & Poulain, F. *FISHERIES IN THE DRYLANDS OF SUB-SAHARAN AFRICA “ Fish come with the Rains ” Building resilience for fisheries-dependent livelihoods to enhance food security and nutrition in the drylands. FAO Fisheries and Aquaculture Circular No.1118*. **1118,** (2016).

111. Battaglini, E. *The Black Sea — A Dramatic Recovery. Environment Matters Annual Review. World Bank*. (2008).

112. Keskin, Ç. *et al.* The Marine Fisheries in Bulgaria's Exclusive Economic Zone, 1950–2013. *Front. Mar. Sci.* **4,** 1–10 (2017).

113. FAO. *Information on Fisheries Management in the Republic of Burundi*. (1999).

114. FAO. Central African Republic: farming and families hit by insecurity. *Food and Agriculture Organization of the United Nations* http://www.fao.org/news/story/en/item/263271/icode (2014).

115. Springer, K. A 400 year old port - with no boats. *BBC Travel* http://www.bbc.com/travel/story/20151110-preservin (2015).

116. Ramdeen, R., Harper, S. & Zeller, D. Reconstruction of total marine fisheries catches for Dominica (1950-2010). *Fish. Catch Reconstr. Islands, Part IV. Fish. Cent. Res. Reports. Sea Around Us Fish. Centre, Univ. Bristish Columbia* **22(2),** 33–41 (2014).

117. Ram, R., Chand, R. V. & Southgate, P. C. An overview of sea cucumber fishery management in the Fiji islands. *Su Ürünleri Derg.* **11,** 191–205 (2016).

118. Beare, D. J. *et al.* Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. *Mar. Ecol. Prog. Ser.* **284,** 269–278 (2004).

119. Moutopoulos, D. K. & Stergiou, K. I. Spatial disentangling of Greek commercial fisheries landings by gear between 1928-2007. *J. Biol. Res.* **18,** 265–279 (2012).

120. Mohammed, E. & Lindop, A. Grenada: Reconstructed Fisheries Catches, 1950-2010. *Fish. Cent. Res. Reports, Univ. Br. Columbia* **86,** 6–9 (2006).

121. FAO. *National Aquaculture Sector Overview. Hungary. National Aquaculture Sector Overview Fact Sheets. Text by Varadi, L. In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 1 January 2003.* (2003).

122. Piroddi, C. *et al.* Reconstruction of Italy's marine fisheries catches (1950-2010). *Fish. Cent. Work. Pap. Ser.* **22,** 1–41 (2014).

123. FAO. *Fishery Country Profile. Jamaica - Structure and Characteristics of the Fishing Industry. Food and AGricultural Organization of the United Nations*. (2005).

124. Aiken, K., Kong, A., Smikle, S., Appeldoorn, R. & Warner, G. Managing Jamaica's queen conch resources. *Ocean Coast. Manag.* **49,** 332–341 (2006).

125. Ojuok, J. E., Njiru, M., Ntiba, M. J. & Mavuti, K. M. The effect of overfishing on the life-history strategies of Nile tilapia, Oreochromis niloticus (L.) in the Nyanza Gulf of Lake Victoria, Kenya. *Aquat. Ecosyst. Heal. Manag.* **10,** 443–448 (2007).

126. McClanahan, T. R., Hicks, C. C. & Darling, E. S. Malthusian overfishing and efforts to overcome it on Kenyan coral reefs. *Ecol. Appl.* **18,** 1516–1529 (2008).

127. SPREP Pacific Regional Environment Programme. *State of the environment report. Government of the Republic of Kiribati*. (2004).

128. Shon, S., Harper, S. & Zeller, D. Reconstruction of Marine Fisheries Catches for the Democratic People's Republic of Korea (North Korea) from 1950-2010. *Fish. Cent. Work. Pap. Ser. Univ. Br. Columbia* **20,** 1–11 (2010).

129. Mathews, C. P., Kedidi, S., Fita, N. I., Al-Yahya, A. & Al-Rasheed, K. Preliminary assessment of the effects of the 1991 Gulf War on Saudi Arabian prawn stocks. *Mar. Pollut. Bull.* **27,** 251–271 (1993).

130. Pauly, D. & Zeller, D. *So long, and thanks for all the fish: The Sea Around Us, 1999-2014 A Fifteen-Year Retrospective*. *Fisheries Centre, University of British Columbia* (2016).

131. FAO NACA SEAFDEC BOBP-IGO. *Tsunami Impact on Fisheries and Aquaculture in Malaysia*. (2005).

132. Adam, M. Declining Catches of Skipjack in the Indian Ocean – Observations from the Maldives. in *Proceedings of the 10th Meeting of the Working Party on Tropical Tuna, Indian Ocean Tuna Commission* 1–2 (2010).

133. Doherty, B., Herfaut, J., Manach, F. Le, Harper, S. & Zeller, D. Reconstructing domestic marine fisheries in Mayotte from 1950-2010. *Fish. catch Reconstr. West. Indian Ocean. 1950-2010* 53–66 (2015).

134. Ramdeen, R., Ponteen, A., Harper, S. & Zeller, D. in *Fisheries catch reconstructions: Islands, Part III. Fisheries Centre Research Reports 20(5). Fisheries Centre, University of British Columbia* 69–78 (2012).

135. Harper, S., Frotté, L., Bale, S., Booth, S. & Zeller, D. in *Fisheries catch reconstructions: Islands, Part I. Fisheries Centre Research Reports 17 (5). Fisheries Centre, University of British Columbia* (eds. Zeller, D. & Harper, S.) 67–76 (2009).

136. Clark, M. Are deepwater fisheries sustainable? — the example of orange roughy (*Hoplostethus atlanticus*) in New Zealand. *Fish. Res.* **51,** 123–135 (2001).

137. Zylich, K., Harper, S., Winkler, N., and Zeller, D. in *Fisheries catch reconstructions: Islands, Part III. Fisheries Centre Research Reports 20(5). Fisheries Centre, University of British Columbia* (eds. Harper, S. et al.) 77–86 (2012).

138. Lingard, S., Harper, S., Ota, Y. & Zeller, D. in *Fisheries catch reconstructions: Islands, Part II. Fisheries Centre Research Reports 19(4). Fisheries Centre, University of British Columbia* (eds. Harper, S. & Zeller, D.) 73–84 (2011).

139. Anticamara, J. A. & Go, K. T. B. Spatio-Temporal Declines in Philippine Fisheries and its Implications to Coastal Municipal Fishers' Catch and Income. *Front. Mar. Sci.* **3,** 1–10 (2016).

140. Bănaru, D., Manach, F. Le, Färber, L., Zylich, K. & Pauly, D. From bluefin tuna to gobies: a reconstruction of the fisheries catch statistics in Romania, 1950-2010. *Fish. Cent. Work. Pap. Ser.* 11 (2015).

141. Mohammed, E., Lindop, A. & Lucia, S. St. Lucia: Reconstructed fisheries catches, 1950 -2010. *Fish. Cent. Work. Pap. Ser. Univ. Br. Columbia* **53,** 1950–2010 (2015).

142. Pena, M., Oxenford, H. A., Parker, C. & Johnson, A. Biology and fishery management of the white sea urchin, Tripneustes ventricosus, in the eastern Caribbean. *FAO Fisheries and Aquaculture Circular No 1056* 1–43 (2010).

143. Itano, D. G. Small-scale fisheries for bottomfish in American Samoa (1961-1987). *SPC Fish. Newsl. #77* 28–32 (1996).

144. Martin, J. I. Fisheries in the Seychelles and Fisheries Agreements with the EU. D. *Directorate-General for Internal Policies of the Union. Policy Department B: Structural and Cohesian Policies* 64 (2011).

145. Doyle, B., Harper, S., Jacquet, J. & Zeller, D. in *Fisheries catch reconstructions: Islands, Part III. Fisheries Centre Research Reports 20(5). Fisheries Centre, University of British Columbia [ISSN* (eds. Harper, S. et al.) **20,** 2080 (2014).

146. Baust, S., Teh, L., Harper, S. & Zeller, D. in *Fisheries catch reconstructions in the Western Indian Ocean, 1950-2010* (eds. Le Manach, F. & Pauly, D.) **23(2),** 129–150 (2015).

147. De Silva, D. A. M. & Yamao, M. Effects of the tsunami on fisheries and coastal livelihood: A case study of tsunami-ravaged southern Sri Lanka. *Disasters* **31,** 386–404 (2007).

148. Hornby, C., Harper, S., MacDonald, J. & Zeller, D. Reconstruction of Suriname'S Marine Fisheries Catches From 1950-2010. *Fish. Cent. Work. Pap. Ser. Univ. Br. Columbia* **49,** 1–29 (2015).

149. Burkhardt-Holm, P., Peter, A. & Segner, H. Decline of fish catch in switzerland: Project fishnet: A balance between analysis and synthesis. *Aquat. Sci.* **64,** 36–54 (2002).

150. Ulman, A., Saad, A., Zylich, K., Pauly, D. & Zeller, D. in *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impacts* (eds. Pauly, D. & Zeller, D.) 406 (sland Press, Washington DC, USA., 2017).

151. Jacquet, J. & Zeller, D. in *Reconstruction of marine fisheries catches for key countries and regions (1950- 2005)* (eds. Zeller, D. & Pauly, D.) **15(2),** 49–60 (2007).

152. Ulman, A. *et al.* From bonito to anchovy: A reconstruction of Turkey's marine fisheries catches (1950-2010). *Mediterr. Mar. Sci.* **14,** 309–342 (2013).

153. Morell, V. Can Science Keep Alaska's Bering Sea Pollock Fishery Healthy? *Science (80-.).* **326,** 1340–1342 (2009).

154. Taylor, G. T. *et al.* Ecosystem responses in the southern Caribbean Sea to global climate change. *Proc. Natl. Acad. Sci.* **109,** 19315–19320 (2012).

155. Rueda-Roa, D. *et al.* Spatial variability of Spanish sardine (Sardinella aurita) abundance as related to the upwelling cycle off the southeastern Caribbean Sea. *PLoS One* **12,** 1–25 (2017).

156. Teh, L., Zeller, D., Zylich, K., Nguyen, G. & Harper, S. Reconstructing Vietnam's Marine Fisheries Catch 1950-2010. *Fish. Cent. Work. Pap. Ser. Univ. Br. Columbia* **17,** 1–37 (2014).

157. FAO. *National Aquaculture Sector Overview. Albania. Text by Cobani, M. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2015).

158. FAO. National Aquaculture Sector Overview. Congo. National Aquaculture Sector Overview Fact Sheets. *In: FAO Fisheries and Aquaculture Department [online]. Rome. Text by Ebounaka, H. . Updated 2 May 2005. [Cited 9 February 2018]* (2005).

159. FAO. *National Aquaculture Sector Overview. Democratic Republic of Congo. National Aquaculture Sector Overview Fact Sheets. Text by Kombozi, G.L.B. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2006).

160. FAO. *Drought characteristics and management in the Caribbean. Food and Agriculture Organization of the United Nations*. (2016).

161. FAO. *National Aquaculture Sector Overview. Ecuador. National Aquaculture Sector Overview Fact Sheets. Text by Schwarz, L. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

162. IFRC. *Emergency Plan of Action Final Report. El Salvador: Drought. International Federation of Red Cross and Red Crescent Societies*. (2015).

163. FAO. FAOSTAT. (2017). Available at: http://www.fao.org/faostat/en/.

164. Christiansen, D. H., Østergaard, P. S., Snow, M., Dale, O. B. & Falk, K. A low-pathogenic variant of infectious salmon anemia virus (ISAV-HPR0) is highly prevalent and causes a non-clinical transient infection in farmed Atlantic salmon (Salmo salar L.) in the Faroe Islands. *J. Gen. Virol.* **92,** 909–918 (2011).

165. Artigas, L. F., Vendeville, P., Leopold, M., Guiral, D. & Ternon, J. Marine Biodiversity in French Guiana : Estuarine, Coastal, and Shelf Ecosystems Under the Influence of Amazonian Waters. *Gayana* **67,** 302–326 (2003).

166. FAO. *Iraq: Agriculture And Livelihoods Needs Assessment In the Newly Liberated Areas of Kirikuk, Ninewa and Salahadin. Food and Agricultural Organization of the United Nations.* (2016).

167. Ponia, B. *A review of aquaculture in the Pacific Islands 1998-2007*. *SPC Aquaculture Technical Papers* (2010).

168. UNEP. Integrated Assessment of Trade-related Policies and Biological Diversity in the Agricultural Sector in Madagascar. in *Integrated Assessment of Trade-related Policies and Biological Diversity in the Agriculture Sector Capacity Building Workshop* https://unep.ch/etb/initiatives/Executive%20Summar (2006).

169. The World Bank. Reducing Disease Risk In Aquaculture. *World Bank. Agric. Environ. Serv.* 119 (2014).

170. FAO. *National Aquaculture Sector Overview. Malta. National Aquaculture Sector Overview Fact Sheets. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2003).

171. Iborra Martin, J. Fisheries in Martinique. *Policy Dep. Struct. Cohesioan Policies. Dir. Gen. Intern. Policies Union* 18 (2007).

172. Soto-Rodriguez, S. A., Gomez-Gil, B. & Lozano, R. 'Bright-red' syndrome in Pacific white shrimp Litopenaeus vannamei is caused by Vibrio harveyi. *Dis. Aquat. Organ.* **92,** 11–19 (2010).

173. FAO. *National Aquaculture Sector Overview. Morocco. National Aquaculture Sector Overview Fact Sheets. Text by Abdellatif, O.; El- Ahdal, M. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

174. FAO. *National Aquaculture Sector Overview. Pakistan. National Aquaculture Sector Overview Fact Sheets. Text by Hayat, M. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

175. FAO. *National Aquaculture Sector Overview. Panamá. National Aquaculture Sector Overview Fact Sheets. Text by Pretto Malca, R. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

176. Andriesse, E. & Lee, Z. Viable insertion in agribusiness value chains? Seaweed farming after Typhoon Yolanda (Haiyan) in Iloilo Province, the Philippines. *Singap. J. Trop. Geogr.* **38,** 25–40 (2017).

177. FAO. *National Aquaculture Sector Overview. Poland. National Aquaculture Sector Overview Fact Sheets. Text by Zakes, Z. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

178. FAO. *National Aquaculture Sector Overview. Kingdom of Saudi Arabia. National Aquaculture Sector Overview Fact Sheets. Text by Odaiby, M. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2015).

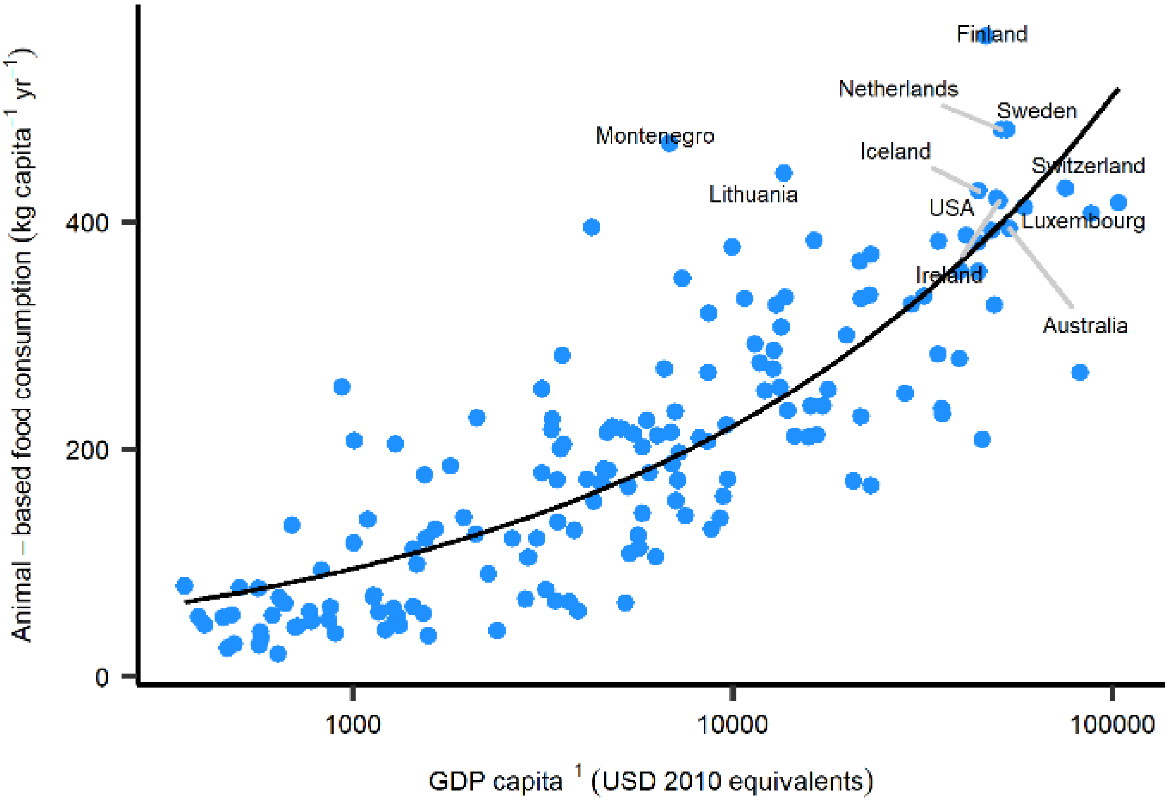
179. FAO. *Review of the State of World Aquaculture. FAO Inland Water Resources and Aquaculture Service, Fishery Resources Division. FAO Fisheries Circular. No. 886, Rev.1. Rome* (1997).

180. Republic of Trinidad and Tobago. Review of the Economy 2002. https://www.finance.gov.tt/wp-content/uploads/2013 (2002).

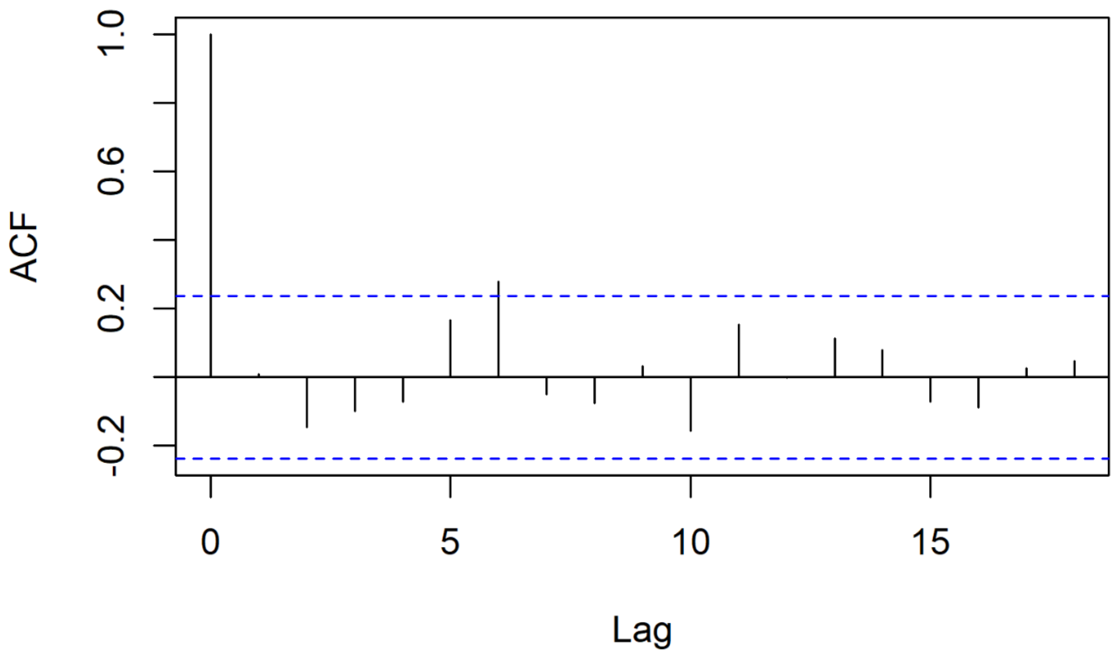
181. FAO. *National Aquaculture Sector Overview. Uruguay. National Aquaculture Sector Overview Fact Sheets. Text by Foti Clavelli, R. In: FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

182. FAO. National Aquaculture Sector Overview. Visión General del Sector Acuícola Nacional - Venezuela (República Bolivariana de). National Aquaculture Sector Overview Fact Sheets. *FAO Fisheries and Aquaculture Department [online]. Rome.* (2005).

Appendix D – Chapter 5 Supplementary Information



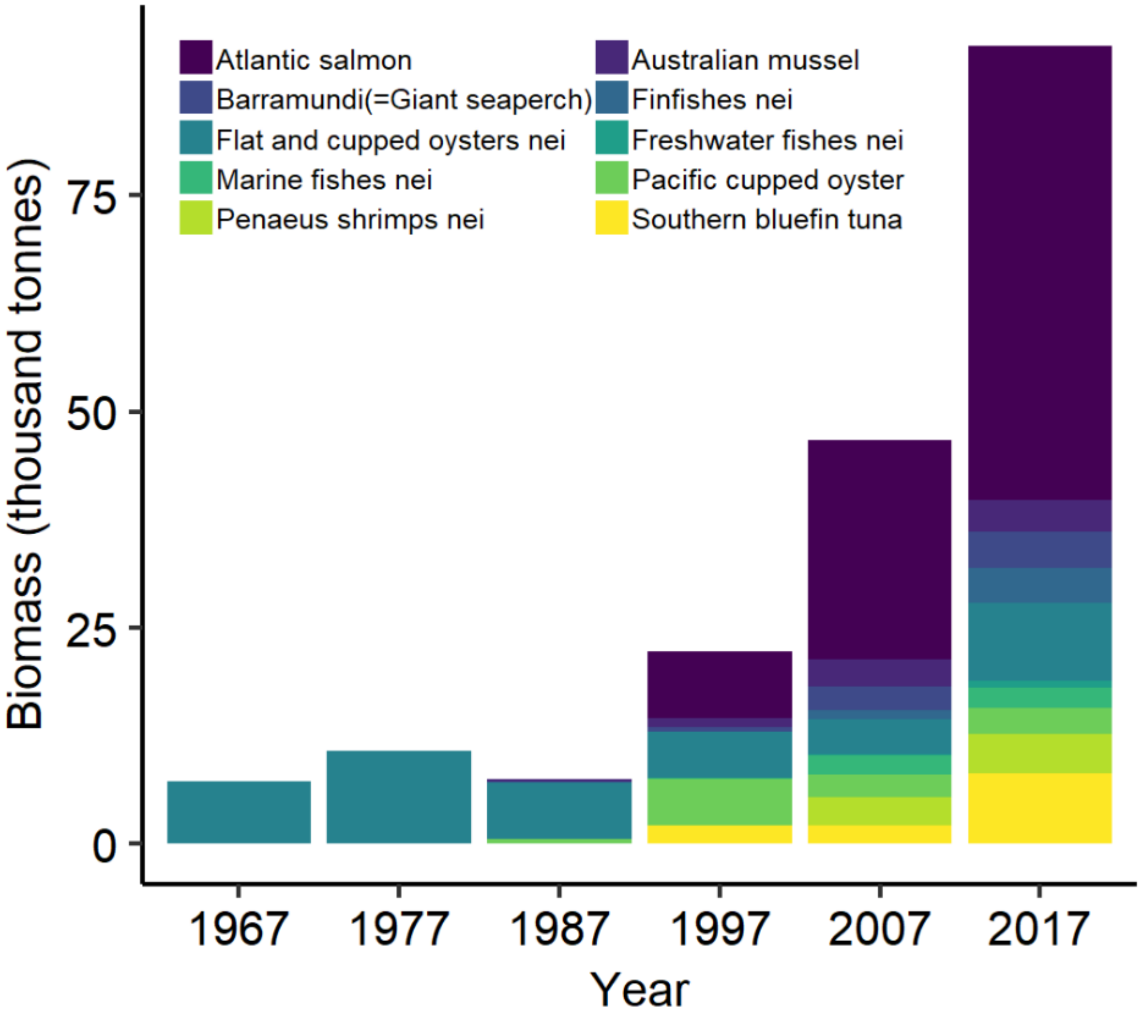
Appendix Figure 11. Global trends in per capita consumption of animal-based foods (fish/seafood, meat, eggs, milk) with wealth (GDP per capita). Note x-axis breaks are on a $\log_{10}$ scale although labels are not. The top 10 countries for animal consumption and Australia (14th) are indicated.



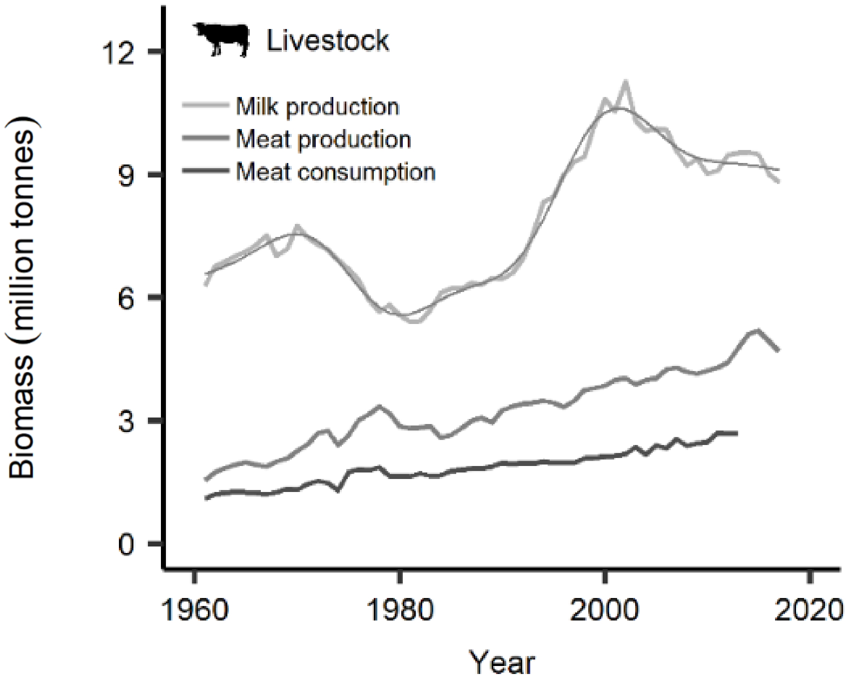
Appendix Figure 12 – Autocorrelation function (ACF) plot of detrended fisheries landings data shown in Figure 19b. Blue dotted lines indicate 95% confidence intervals.

Appendix Table 7- BDS testing of detrended fisheries landings data. Greyed cells are p-values from BDS test statistics

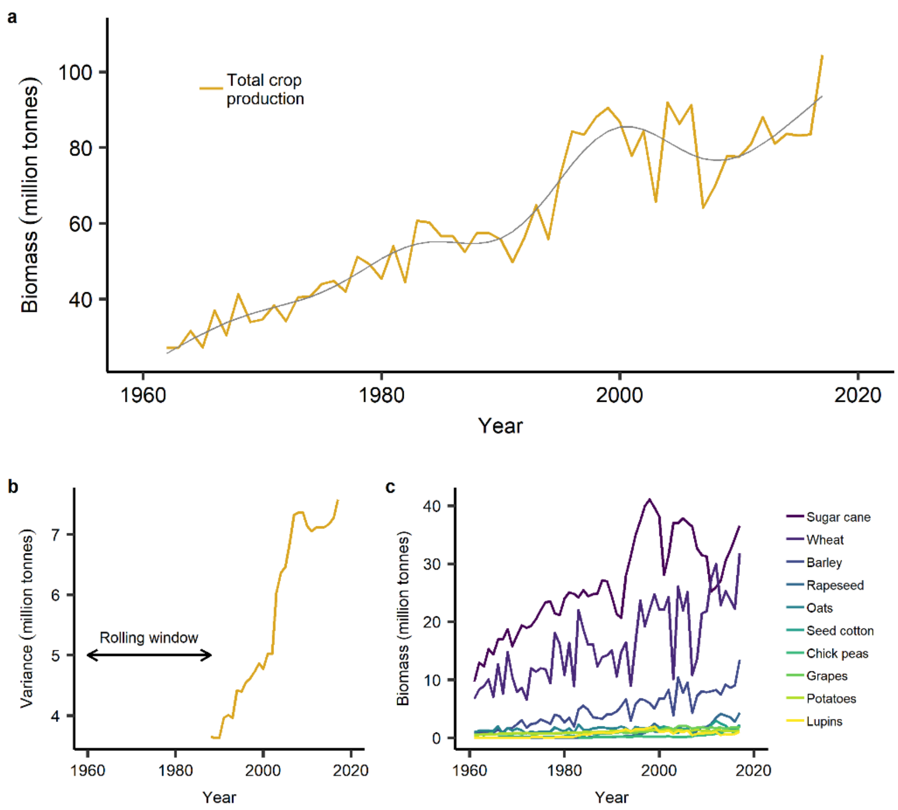
Embedding dimension	**BDS statistic ε (Standard Deviation)**		
	0.5	**0.75**	**1**
2	1.0738	0.6347	0.4749
	0.2829	0.5256	0.6348
3	1.8333	0.6980	0.8395
	0.0668	0.4852	0.4012



Appendix Figure 13 – Temporal trends in Australia aquaculture production and species composition. Species presented limited to top 10 species by production volume in 2017.



Appendix Figure 14 – Temporal trends in Australian meat and milk production and consumption.



Appendix Figure 15 –Variance in Australian crop production. a) Total production time series with fitted generalized additive model (GAM) b) Variance of GAM residuals c) Production trends across Australia's top 10 crop species.

Appendix E – Additional publications during PhD

Published works

Blanchard, J.L., Watson, R.A., Fulton, E.A., **Cottrell, RS,** Nash, K.L., Bryndum-Buchholz, A., Büchner, M., Carozza, D.A., Cheung, W.W., Elliott, J. and Davidson, L.N., Dulvy NK, Dunne JP, Eddy TD, Galbraith E, Lotze HK, Maury O, Muller C, Tittensor DP, Jennings, S (2017) Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. ***Nature Ecology & Evolution***, 1(9), p.1240.

BS Halpern, **Cottrell RS**, Blanchard JL, Bouman L, Froehlich HE, Gephart JA, Jacobsen NS, Kuempel CD, McIntyre PB, Metian M, Moran DD, Nash KL, Tobben, Williams DR (2019). 'Putting all foods on the same table: Achieving sustainable food systems requires full accounting' ***Proceedings of the National Academy of Sciences.***
doi/10.1073/pnas.1913308116

Singh, G.G., Hilmi, N., Bernhardt, J.R., Cisneros Montemayor, A.M., Cashion, M., Ota, Y., Acar, S., Brown, J.M., **Cottrell, R**, Djoundourian, S. and González‐Espinosa, P.C., Lam V, Marshall N, Neumann B, Pascal N, Reygondeau G, Rocklov J, Safa A, Virto LR, Cheung W (2019). Climate impacts on the ocean are making the Sustainable Development Goals a moving target travelling away from us. ***People and Nature***. 00:1–14
https://doi.org/10.1002/pan3.26

Alexander, K.A., Hobday, A.J., Cvitanovic, C., Ogier, E., Nash, K.L., **Cottrell, R.S.,** Fleming, A., Fudge, M., Fulton, E.A., Frusher, S, Kelly, R., Macleod CK, Pecl GT, van Putten I, Vince J, Watson RA, 2019. Progress in integrating natural and social science in marine ecosystem-based management research. ***Marine and Freshwater Research,*** 70(1), pp.71-83.

Kelly, R., Cottrell, R.S., Mackay, M. et al. (2017) Kathleen Schwerdtner Máñez and Bo Poulsen (eds): Perspectives on oceans past: a handbook of marine environmental history. Reviews in Fish Biology and Fisheries. 27 (1) 285-286. doi.org/10.1007/s11160-016-9462-x

Works submitted for review

Blanchard JL, **Cottrell RS,** Watson RA, Rousseau Y, Alexander KA, Bradshaw N, Carter CG, Dhalgren TG, Falconer R, Farmery A, Hornborg S, Macleod C, Nash KL, White C, Cameron DD. Addressing terrestrial limits to marine aquaculture growth. ***Science Policy Forum.*** *In Review*

Singh GS, **Cottrell RS,** Eddy, T, Cisneros-Montemayor AM. Governing the Land-Sea Interface through Transition Management and Assessing Interlinkages of the Sustainable Development Goals. ***Frontiers in Marine Science.*** *In Submission*

Appendix F – Published Works from Thesis

See next page

Cottrell, R. S., Fleming, A., Fulton, E. A., Nash, K. L., Watson, R. A., Blanchard, J. L., 2018. Considering land–sea interactions and trade-offs for food and biodiversity, Global change biology, 24(2), 580-596

nature sustainability

ANALYSIS

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Food production shocks across land and sea

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Sudden losses to food production (that is, shocks) and their consequences across land and sea pose cumulative threats to global sustainability. We conducted an integrated assessment of global production data from crop, livestock, aquaculture and fisheries sectors over 53 years to understand how shocks occurring in one food sector can create diverse and linked challenges among others. We show that some regions are shock hotspots, exposed frequently to shocks across multiple sectors. Critically, shock frequency has increased through time on land and sea at a global scale. Geopolitical and extreme-weather events were the main shock drivers identified, but with considerable differences across sectors. We illustrate how social and ecological drivers, influenced by the dynamics of the food system, can spill over multiple food sectors and create synchronous challenges or trade-offs among terrestrial and aquatic systems. In a more shock-prone and interconnected world, bold food policy and social protection mechanisms that help people anticipate, cope with and recover from losses will be central to sustainability.

Food production shocks pose significant challenges for the United Nations Sustainable Development Goals (SDGs)[1] because of their potential to disrupt food supply and security, livelihoods, and human well-being[2–7]. A wide range of social and ecological pressures on food systems can drive shocks through direct or indirect mechanisms. For example, droughts or floods can rapidly increase the mortality of crops, livestock or farmed fish, whereas sudden outbreaks of violent conflict may prevent farmers or fishers from accessing their production systems[7,8]. Prolonged overfishing can also produce unexpected, sudden losses in catch as exploited fish populations are pushed towards ecological tipping points, after which stock collapse occurs[9]. People's vulnerability to shock events rests on their capacity to adapt, the scale and frequency of shocks, and their dependence on the affected sector[10]. Given that millions of people worldwide simultaneously depend on agricultural and seafood sectors for food and livelihood[11,12], understanding national vulnerabilities to shocks requires a complete picture of exposure across sectors on land and at sea. Yet, studies on food production shocks to date largely deal with agricultural and seafood commodities in isolation[2,7,13]. Integrated understanding is required to assess the cumulative risks to sustainability across all food sectors in the face of environmental change and human population growth.

We investigated historical global trends in exposure to, and drivers of, food production shocks across crop, livestock, fisheries and aquaculture sectors from 1961–2013. We used an established, standardized approach to identify shocks and their drivers in national production data taken from the United Nations Food and Agricultural Organization (FAO) and other published sources. Using local regression models, we identified shocks through breaks in the autocorrelation structure of a time-series, and coupled detection with a literature review of in-country events at the shock point. Here, we map global shock frequency and co-occurrence, and highlight the different ways shocks can permeate multiple food production sectors or drive trade-offs across them.

Global trends in food production shocks

From 741 available food production time-series (crops = 187; livestock = 190; fisheries = 202; aquaculture = 162), we detected 226 shocks across 134 nations. When pooled, we found agricultural sectors (crop and livestock) to be slightly more shock prone than aquatic sectors (fisheries and aquaculture) over the 53-year period (0.31 versus 0.29 shocks per country, respectively). Shock frequencies were regionally distinct within sectors, with some areas experiencing shocks far more frequently than others (Fig. 1). Shock frequencies were highest in South Asia for crops (Fig. 1a), the Caribbean for livestock (Fig. 1b), Eastern Europe for fisheries (Fig. 1c) and South America for aquaculture (Fig. 1d). Importantly, some regions experienced a high frequency in more than one sector. For example, South Asia experienced one of the highest shock frequencies to livestock as well as crops, and the Caribbean experienced a high frequency of fisheries shocks alongside livestock systems. Therefore, while there is varying exposure to production shocks within sectors, in several regions, patterns of high shock frequency overlap and create areas of high cumulative exposure to production shocks across multiple fronts.

The frequency of shocks has increased across all sectors at a global scale. In our results, annual shock frequencies fluctuated considerably over time, yet decadal averages, minimums and maximums increased steadily from the 1960s and 1970s (Fig. 1e–h). We did not detect any shocks to aquaculture production until the early 1980s, probably due to its nascence, but decadal shock rates have risen faster and to a level higher than in any other sector since (Fig. 1h). Increasing shock frequency is a food security concern in itself. Conflict-related shocks across sub-Saharan Africa and the Middle East since 2010, combined with adverse climate conditions, are responsible for the first uptick in global hunger in recent times[4]. While the human impact of shocks depends on the degree to which livelihoods in a region or country depend on food production and the variation in vulnerability among households[4], increased

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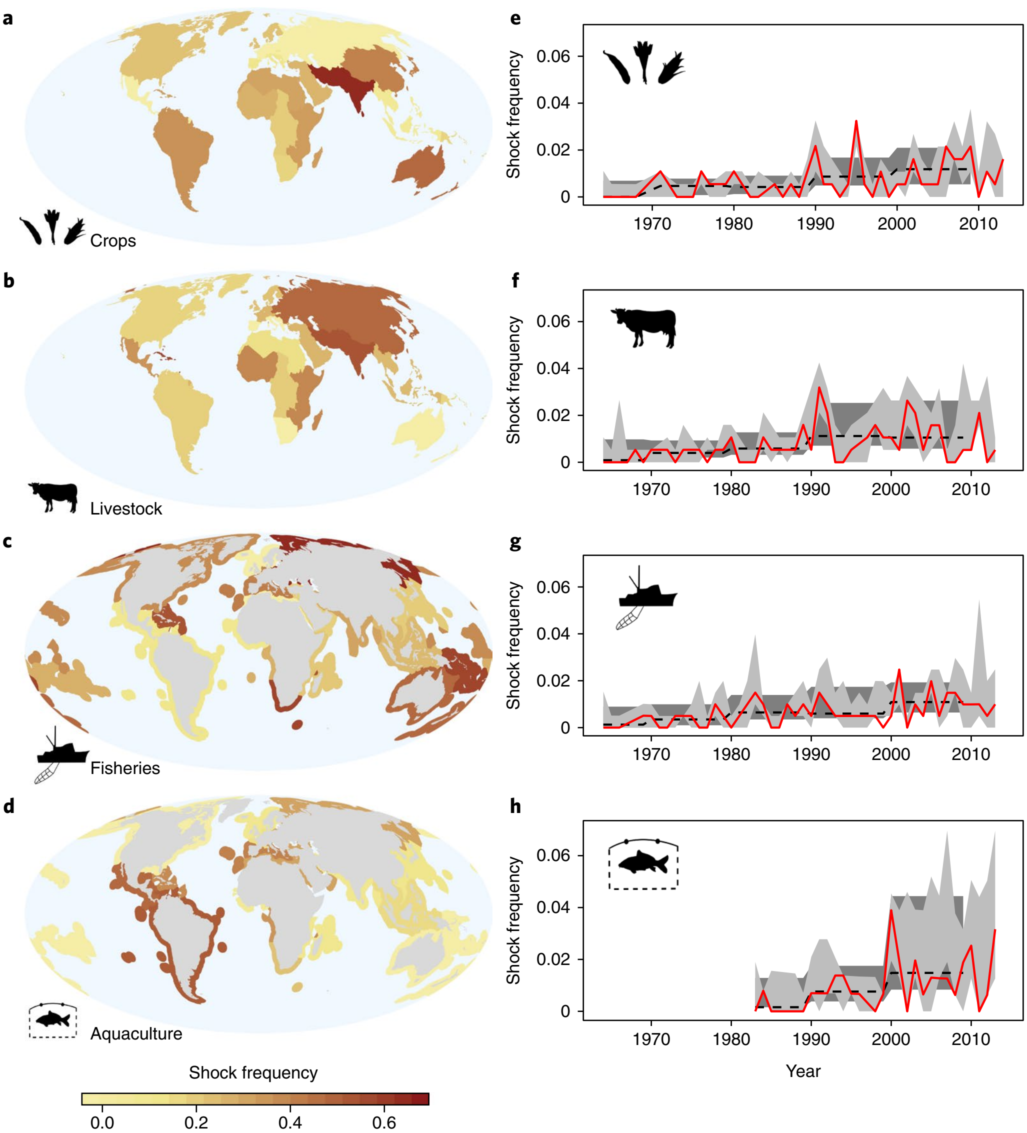

Fig. 1 | Trends in food production shock frequency in crop, livestock, fisheries and aquaculture sectors from 1961–2013. a–h, Spatial (**a–d**) and temporal (**e–h**) trends for crops (**a** and **e**), livestock (**b** and **f**), fisheries (**c** and **g**) and aquaculture (**d** and **h**). Regions include North America, Central America, the Caribbean, South America, Northern Europe, Western Europe, Southern Europe, Eastern Europe, North Africa, West Africa, Central Africa, Southern Africa, East Africa, Western Asia, South Asia, East Asia, Southeast Asia, Melanesia, Micronesia, Australia and New Zealand, and Polynesia. The red lines in the time-series indicate the annual shock frequency from the shocks identified in this study. The light grey confidence interval describes the plausible range of frequencies under different combinations of LOESS model span (0.2–0.8), production baseline durations (3, 5, 7 or 9 years) and types of averaging used for the baseline (mean or median). The dashed black line is the decadal mean of the red line. The dark grey band is the decadal minimum and maximum of the confidence interval.

frequency reduces the time for recovery between events. Smaller windows for recovery hinder coping strategies, such as the accumulation of assets that can be sold during times of hardship, and can ultimately negatively influence the resilience of producers and communities to shocks[4].

Drivers of production shocks across land and sea

Extreme weather events and geopolitical crises were the dominant drivers of shocks in our analysis, but the relative importance of drivers varied across sectors (Fig. 2). Over half of all shocks to crop production systems were a result of extreme weather events (largely drought; Fig. 2), reinforcing concern about the vulnerability of arable systems to climatic and meteorological volatility across the globe[14]. We also found extreme weather to be a major driver of shocks to livestock (23%), particularly where reductions to feed occurred. For instance, severe summertime droughts in Mongolia in 2001 and 2010 reduced fodder and feed availability, compromized livestock condition and led to mass mortality events during cold winter extremes[15]. Diseases such as foot and mouth also contributed to 10% of livestock shocks. However, geopolitical crises, such as economic decentralization in Europe or conflict in sub-Saharan Africa, accounted for the greatest proportion (41%) of the livestock shocks in our analysis (Fig. 2).

In contrast, drivers of seafood production shocks were more diverse than for terrestrial systems (Fig. 2). For fisheries, overfishing was responsible, at least in part, for 45% of shocks detected in landings data. However, geopolitical crises contributed to 23% of fisheries shocks, climate/weather events to 13% and policy changes to 11%. Shocks driven by policy changes can reflect positive interventions, but may also be a response to declining resources. In the

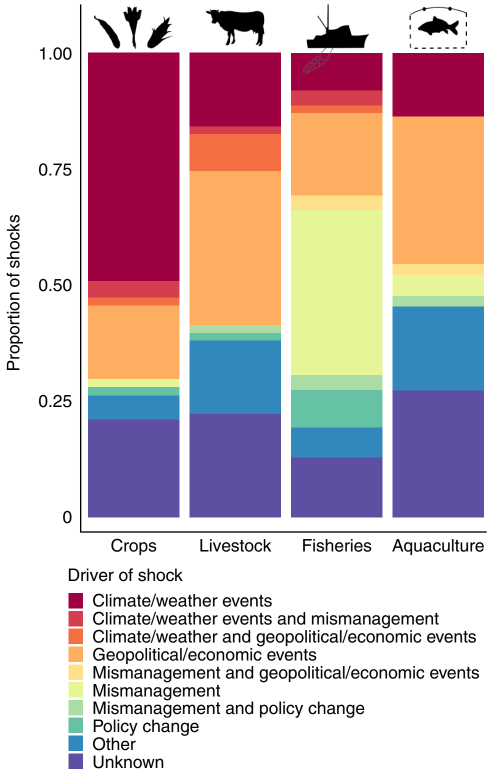

Fig. 2 | Drivers of food production shocks. Relative proportions for the drivers indicated in the legend are shown for the crop, livestock, fisheries and aquaculture sectors.

aquaculture sector, while disease (included in the category 'other') was the most common individual driver (responsible for 16% of shocks overall), a spectrum of geopolitical stressors was behind one-third of aquaculture shocks, from state dissolution to violent conflict and declining competitiveness in export markets.

Patterns of driver influence differed across regions (Supplementary Fig. 1). For example, in South Asia, where agricultural shocks were most frequent, nearly all crop and livestock losses were driven by flood or drought. In contrast, in sub-Saharan Africa, where the greatest burden of hunger still persists[4], geopolitical and economic crises were the leading drivers of agricultural shocks (Supplementary Fig. 1). In seafood sectors, the regional diversity of driver types was more consistent. In wild systems, overfishing and geopolitical drivers contributed to numerous shocks across Europe, sub-Saharan Africa and East Asia. For aquaculture, disease was the primary driver in Europe and Latin America, but geopolitical instability was the main driver of shocks to aquaculture in East Asia, the Middle East and North Africa (Supplementary Fig. 1). Therefore, while we highlight dominant shock drivers for each sector at a global scale, we reiterate that challenges for increasing food production will vary greatly from place to place.

The reason for the increase in shock frequency through time across sectors is not clear, in part because many potential factors (including the quality of reporting) have changed and increased over the time period. However, crop production shocks driven by extreme weather became more frequent in our results over time (Supplementary Fig. 2). In the livestock, fisheries and aquaculture sectors particularly, the diversity of drivers increased from the 1970s (Supplementary Fig. 2). As food systems become increasingly globalized and interdependent, a greater diversity of exogenous shocks may influence them over time[16]. For instance, livestock disease is increasing globally, driven largely by a rapid rise in the demand for meat, the incursion of livestock in natural systems, intense farming practices, and the mass movement of animals and people[17]. The nature of interdependencies among sectors is also changing[18]. Demands for feed now tightly couple aquaculture to both capture fisheries and crop systems[19], and the production challenges each of these encounter are therefore closely linked. Furthermore, financial institutions motivated by socioeconomic drivers disconnected from their geographies of influence increasingly sway producer investments and decisions with complex or unknown consequences for production stability or sustainability[20].

Co-occurrence and spillover across terrestrial and aquatic sectors

Climate events, violent conflict or other social and ecological stressors can create complex synchronous or lagged effects across different systems[4]. Therefore, a single stressor could elicit numerous shocks across different food sectors but not always at the same time. So, while we would not necessarily expect shocks from the same stressor to coincide at the exact shock point (year), we would expect to see clumping of shocks within broader time-periods. Co-occurrence appeared in our data from the early 1990s, and more frequently in the latter half of our time-series (Fig. 3a). Of the 134 nations affected by shocks in our analysis, 22 experienced shocks in multiple sectors during the same five-year period (Fig. 3b). We recognize that these trends are influenced by the length of the time intervals used in Fig. 3 and do not reflect changes in other sectors not detected as a shock (although they may be a response or a driver of shocks detected here). Overlapping shock occurrence in this way allows us to identify and further examine the more detailed conditions underpinning the occurrence of multi-sectoral shocks.

Shocks spanning multiple sectors were often driven by geopolitical events. For example, the loss of Soviet-linked subsidies and reduced export markets in Albania during the fall of communism resulted in large declines in crop, fisheries and aquaculture production[21–23]. North Korea experienced lagged impacts from economic fall-out from the Union of Soviet Socialist Republics dissolution by the mid-1990s, and extreme flooding exacerbated the scale of production losses on land. The resulting famine led to the deaths of over 200,000 people[24,25]. In Mali, internal conflict from 2011 onwards displaced farmers and fishermen alike by limiting access to rivers and farms directly, or through disruption to supply chains[26]. Nonetheless, the geography of the shock, magnitude of the driver, importance of the affected systems for national production, and adaptive (for example, coping strategies), absorptive (for example, reserves, assets and capital) or transformative capacities (for example, governance mechanisms)[4] of affected communities will all influence how a shock manifests across different food systems. Taking further examples from Fig. 3, we illustrate how the social-ecological dynamics of both the country and the shock can yield variable responses across sectors (Fig. 4).

Drivers of shocks can create similar or opposing responses in production across multiple sectors, revealing links between terrestrial and aquatic systems. In both Kuwait (Fig. 4a) and Afghanistan (Fig. 4b), different shock drivers at different scales created similar national-level responses spanning terrestrial and aquatic production. The invasion of Kuwait by Iraq in late 1990 and the subsequent conflict with the United States and its allies was a huge nationwide disturbance, caused widespread devastation to agricultural land, and the removal of the majority of Kuwaiti fishing vessels ceased commercial fishing[27]. Rapid declines in crop, livestock and fisheries production occurred from 1990, with shocks detected in both livestock and fisheries time-series (Fig. 4a). In Afghanistan, a severe drought from 2000–2002 decimated cereal production, particularly in the country's north. Large increases in animal diseases and reduced fodder severely affected production for pastoralists[28], and we detected a shock to fisheries landings at the same point (Fig. 4b). However, the similar declines across sectors disguise the differences

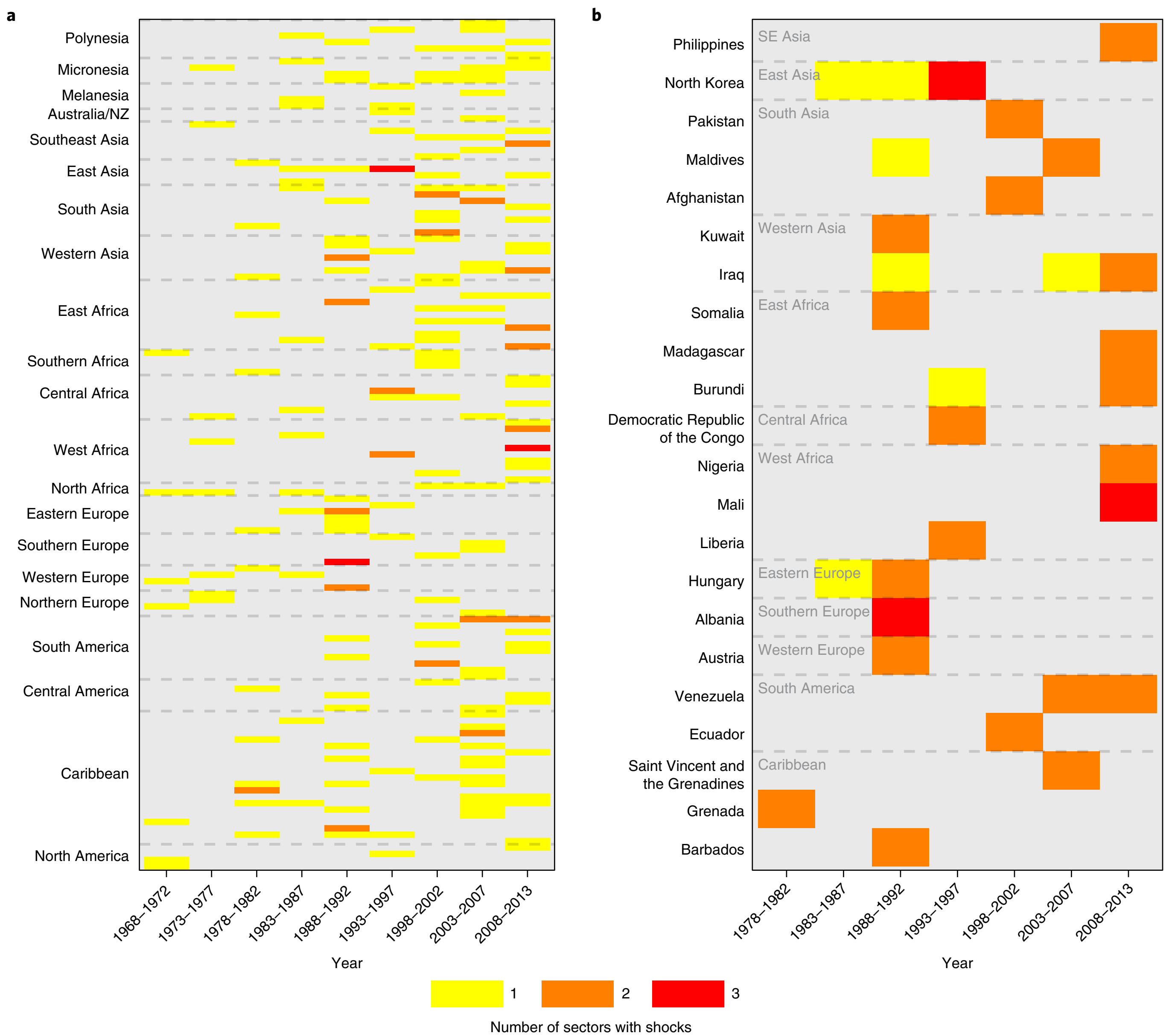

Fig. 3 | Heat map of shock co-occurrence across terrestrial and aquatic food sectors through time. a, Global extent of co-occurrence in all countries affected by shocks in our analysis, grouped by subregion. NZ, New Zealand. **b**, Isolated countries where shocks occurred across multiple sectors during the same five-year period.

in vulnerability. Disturbances at the scale of the Gulf War are rare events, whereas droughts are frequent across Western Asia. In Afghanistan, its landlockedness and the absence of marine fisheries leaves national food production more vulnerable to drought.

In contrast, divergent responses to extreme weather in Dominica illustrate the potential for land–sea trade-offs when human adaptation measures shift resource use across sectors. Repeated damage to farmland from tropical storms during the 1970s pushed more of the nation's farmers into fishing for a primary income source[29]. After Hurricane David decimated the banana crop in 1979, fisheries landings increased dramatically from 1980, followed by a rapid decline in 1983 (Fig. 4c), probably driven by overfishing leading to stock collapse in nearshore waters[29]. Shifts between land and sea following a shock were rare in our analysis of national time-series. It is possible that Dominica's small size and high dependence on a single crop for livelihoods of the rural poor (who have few absorptive strategies for coping with crises)[30] contributed to this response. However, it is likely that these switches occur much more widely at smaller scales, given the prevalence of joint dependence on fisheries and agriculture worldwide[11], and because small-scale fisheries are often used to buffer the effects of extreme events[31].

In Ecuador, shocks occurred at similar points in both crop and aquaculture systems, with seemingly unrelated proximate drivers if investigated solely from single-sector perspectives (Fig. 4d). The strong El Niño Southern Oscillation event of 1998 led to widespread flood damage to croplands across Ecuador[32], detected as a shock in our time-series, and at the same time, a large reduction in coastal fisheries landings occurred (Fig. 4d), although this was not detected as a shock due to the variable nature of the Humboldt system[2]. While there were reports of flood damages to shrimp farms in 1998, two years later, we detected a shock to aquaculture production because of dramatic declines in the shrimp industry. These declines are consistent with the reports of a white-spot syndrome outbreak, which severely affected the industry in 2000[33]. We could

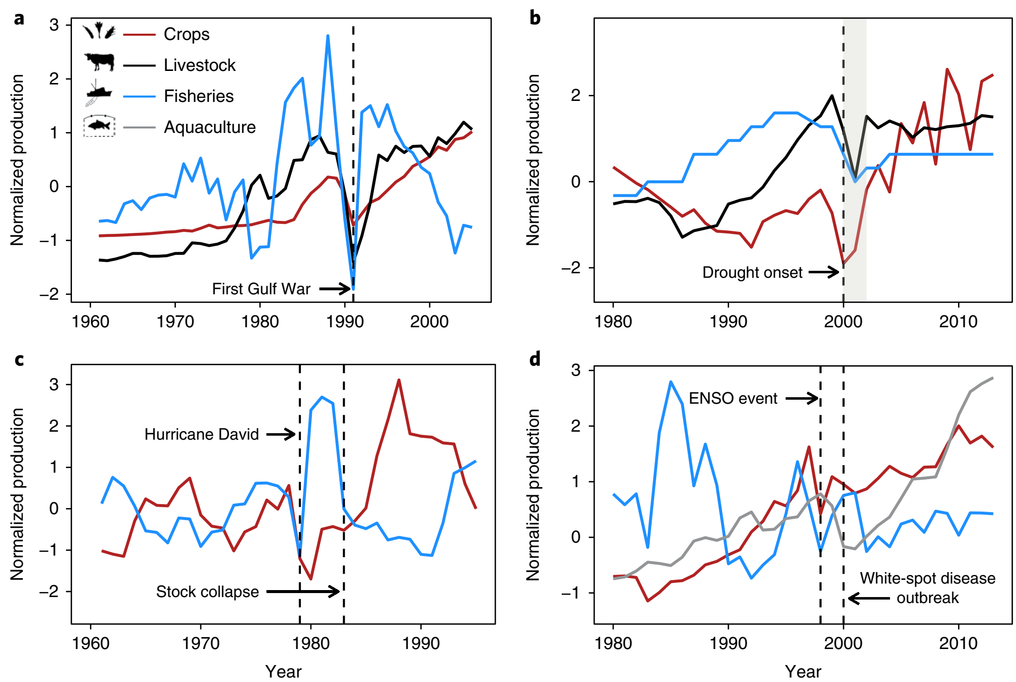

Fig. 4 | Case studies of shock spillover, trade-offs, and co-occurrence across terrestrial and aquatic sectors. **a**, Invasion of Kuwait during the Gulf War. **b**, Severe drought in Afghanistan. **c**, Land–sea switches following Hurricane David in Dominica. **d**, El Niño-driven floods on land followed by an outbreak of white-spot disease in shrimp farms in Ecuador. ENSO, El Niño Southern Oscillation.

find no documented link between the El Niño event and the disease outbreak; however, abnormally warm coastal waters on the Pacific South American coast are associated with both El Niño events and the rapid spread of the white-spot Syndrome virus[34]. Irrespective of whether these shocks were connected or not, an increased co-occurrence because of linked or independent drivers becomes problematic for communities with a reduced capacity to deal with these dual impacts.

Challenges and potential for sustainable development in a shock-prone world

Shocks across multiple sectors pose significant threats to improving global food security, as well as other sustainability targets. For example, one target within SDG 2 (zero hunger) is to strengthen adaptive capacity in the face of climate change and extreme events[1]. For many people, livelihood diversification between agriculture and fisheries is a key strategy in alleviating the impacts of production shortfalls[11,35,36], yet shocks across multiple sectors compromise these options. A lack of viable alternatives can drive people to derive food or income from other sources, with unpredictable sustainability consequences. The declines in large mammal populations in West Africa during times of low fish supply or after the collapse of agricultural systems in the Soviet Union are clear examples[37,38]. Trade-offs such as this across sectors, including the example from Dominica (Fig. 4c), present significant challenges for achieving other sustainability targets. Unpredictable shifts among sectors create interactions among the goals for life on land, life below water, or responsible production and consumption[1], for instance. Furthermore, as shock rates increase across all sectors, the capacity for shocks to co-occur increases simultaneously.

On a global scale, increased shock frequency may pose a threat to the resilience of the global food system through impacts on trade. Nearly one-quarter of food, agricultural land and freshwater resources are accessed through trade[6], and a number of countries are dependent on imports to meet the food demands of their population[39]. Trade dependency is also becoming more regionally specialized, with some major breadbaskets the sole suppliers of commodities to other nations. For example, Thailand currently provides over 96% of rice imports to a number of West African countries[40]. The high dependence on just a handful of producers for some countries highlights future vulnerability. Producing countries often reduce or ban exports during production crises to protect domestic supply, endangering import-dependent trade partners[5,6,39,40]. If shock frequencies continue to increase and major producing nations are affected, a shift to a state of reduced exports is plausible at a global level. Increased commodity prices linked to global scarcity would favour higher-paying nations[40], leaving low-income, trade-dependent countries in jeopardy. In the case that a higher frequency of shocks is influencing the stability of trade, we might expect to see increased temporal variability in either trade or price data. Whether or not these signals are present in the available data warrants further investigation.

Country-level differences in vulnerability to external or domestic production shocks mean that the challenges posed by them are uneven across regions and commodities. For example, frequent shocks in small Caribbean livestock sectors will have variable consequences across the different regional economies, yet a shock in major producers such as Argentina may influence supply for multiple trade partners around the world[41]. Comparing across commodities, frequent or severe crop shocks in major breadbaskets such as South Asia can have far-reaching consequences for global food availability and access[5], but relatively small shocks to fish landings in small-island developing states may have equally negative effects on nutrition[12,42]. The diverse sources of threat across land and sea from domestic or foreign sources highlights a pressing need to improve resilience to shocks in both agricultural and seafood sectors.

Building resilience at a global level will require more proactive national food and trade policies. Investing in climate-smart food systems that exploit ecosystem services to mitigate extreme -events will be increasingly important[43]. For instance, increasing the diversity of plant and animal breeds/varieties can minimize vulnerability to disease; integrating agroforestry into farm systems and enhancing soil quality can improve recovery times after drought and floods[3,43]. Concerted efforts should be made in import-dependent countries to build domestic food reserves to buffer the effects of supply losses when trade partners reduce exports during production shocks[6]. Moreover, international trade policies should aim to disincentivize behaviours that exacerbate the impacts of production shocks, such as commodity hoarding and export bans. Such policy is especially important for major food producers, such as the USA, India or China, whose trade networks have greater global influence on food supply[6]. Maintaining fair and open trade should be made a priority in addressing global hunger.

In shock-prone areas, a number of social protection mechanisms will be key. These mechanisms may help nations, communities and households prevent and anticipate shocks, cope with them and recover[4]. For example, conflict-related shocks remain the biggest barrier to food security in the world's most food-insecure regions[4,7]. Greater understanding of the causes of conflict in different areas is central to prevention[4]. New early-warning systems for violence are already underway[44]. During times of crisis, timely food and cash transfers, and food or cash for work programmes, show promise throughout sub-Saharan Africa[45]. For those displaced, to speed up recovery and close yield gaps, participatory planning and post-conflict support, such as tools, seeds or skills training, is crucial[4,46]. Weather-indexed insurance is another innovative tool to protect producers against loss of income or food access during adverse conditions[47], and will be particularly important if extreme events become more frequent[48].

Increased investment in food systems research to improve resilience to shocks is urgently required under climate change. Continued development of drought and pest-related resistance in key crops is crucial[49], but understanding and addressing barriers to uptake in food-insecure countries is equally important[50]. The same applies where fish farming could increase resilience to external shocks in vulnerable nations[42], but barriers that limit industry growth must be overcome. In commercial-scale aquaculture systems, improvements in open data and new sequencing technologies can help us understand the microbial conditions surrounding disease emergence, which is fundamental to meeting increasing global seafood demands[51]. Without learning to mitigate and adapt to the effects of increased volatility in food systems, global goals to end hunger and protect our natural ecosystems may be out of reach.

The trends discussed here almost certainly under-represent the frequency of production shocks. Aggregation of production data to the country level smooths out sudden production losses that are locally isolated or restricted to a single food type. This is particularly true in large countries, such as the United States or Australia, where food is grown over large and diverse landscapes. Small-scale, unreported food systems (for example, some inland and marine fisheries or aquaculture, backyard farm systems and wild meat sources) are also not included in the data used in this analysis. Although this is a recognized weakness, the data used here represent the best source of production data with global coverage across multiple sectors. Nevertheless, localized shocks or shocks to small-scale systems are still of concern for the livelihoods and food security of communities dependent on them.

Achieving the SDGs by 2030 will require addressing drivers of food production shocks and derived threats. With shock frequency increasing across sectors, the likelihood of shock co-occurrence increases, particularly in hotspots of shock exposure. Production challenges will be felt most strongly by those with a lower capacity to adapt to or absorb shocks. With extreme weather events predicted to increase into the future, potentially interacting with civil unrest, achieving food security in regions most exposed to shocks may hinge on successful social protection mechanisms to help people cope and recover. Fundamental shifts towards shock-resilient food systems will require considerable but achievable changes to how we grow and trade food. Integrating and understanding the links between land and sea will be critical for programmes and research aiming to affect progress towards food security and sustainable development.

Methods

To identify and compare shock occurrence among fundamentally different systems (agriculture and seafood), we adopted the paired statistical and qualitative approach of Gephart et al.[2]. This method identifies shocks through breaks in the autocorrelation structure of a time-series and combines this with a literature search for the probable driver of the shock. Alternative studies have used pre-published datasets on extreme events to understand responses in production data[31]; however, this skews the focus towards drivers with plentiful data—often terrestrial and biophysical events, such as floods, droughts or cold fronts. Others have also used the trade in virtual water to study shocks in agricultural systems[13], but this largely eliminates the marine component of our food system. Reliance on statistical detection in production data avoids specificity, making it a standardized approach applicable across crop, livestock, fisheries and aquaculture sectors.

Data sources. We used a range of food production data from the FAO, combined with published production datasets, for our analysis. We used crop and livestock data from the FAOSTAT production quantity 1961–2014 dataset (http://www.fao.org/faostat/en/)[52]. Crop types included cereals, coarse grains, fruits, roots and tubers, pulses, tree nuts, and vegetables. Livestock included total meat, milk and egg production from bovine, poultry, swine, mutton and goat sources. We used the FAO FishStat database[53] for inland and marine aquaculture production, and inland fisheries landings data (the 1950–2015 Global Production dataset: www.fao.org/fishery/topic/166235/en). We used marine fish landings data from Watson[54] to account for estimates of large-scale, small-scale, and illegal, unregulated and unreported landings. Fisheries data included all landed finfish, crustaceans and molluscs. Aquaculture data included all farmed finfish, crustaceans, molluscs and algae. While we recognize that the under-reporting of small-scale production across all sectors is a limitation of the FAO data, they provide global coverage of production across multiple sectors, and the detection of shocks relies on overall trends in data rather than absolute production values. We obtained country shapefiles used for mapping global patterns from Natural Earth (https://www.naturalearthdata.com/), and adapted exclusive economic zone shapefiles from Marine Regions (http://www.marineregions.org/)[55]. We performed all data analyses using R statistical software[56].

Detecting shocks and identifying drivers. For all countries, we aggregated production to total annual values from 1961–2013 across all of the commodity types described above for crop, livestock, fisheries and aquaculture sectors. We fitted local polynomial regression (LOESS) models with a span of 0.6 to aggregated annual production data for all countries and sectors. We regressed model residuals against lag-1 residuals, and we deemed any outliers in this regression (quantified as data points with a Cook's distance of >0.3) to be shocks (Supplementary Fig. 4). Given that only production losses are of concern for food security, we only considered shock points associated with a loss in production relative to a previous 7-year median production baseline.

Consistent with the approach by Gephart et al.[2], for each shock detected, we calculated the size of a shock and its recovery time for comparisons across sectors and regions (Supplementary Fig. 1). The shock size equals the loss in production (in tonnes) relative to the previous 7-year median baseline. The recovery time for the shock was calculated as the number of years taken to increase back to at least 95% of this baseline. Some shocks did not recover by the end of the time-series and we highlight these individual shocks in Supplementary Table 1. We calculated shock frequencies for each geographical region by dividing the number of shocks detected from 1961–2013 by the number of time-series used for detection. For annual shock frequencies, for every sector, we divided the number of shocks detected for a given year by the number of countries producing in that year. This approach compensates for different numbers of countries within each region, and the increasing number of countries producing through time.

Adopting a qualitative approach to identifying the drivers of production shocks helps account for and recognize the multiple and complex social and ecological factors contributing to an event. For a detected shock, we searched peer-reviewed and grey literature (for example, NGO reports, news articles, and so on) for the probable causes, or drivers, of each individual shock. Each shock was assessed independently, disaggregating production data into individual commodities to identify the species affected and check our analysis, which allowed greater specificity to our search. We only attributed a driver to a shock when our search returned a documented event or set of conditions where a negative effect on agricultural or seafood sectors (dependent on the sector affected) was explicitly mentioned at, or just before, the shock point (that is, the documentation stipulated the link rather than us establishing purely correlative trends). The combination of quantitative and qualitative methods adopted by Gephart et al.[2] provides complimentary approaches where purely data-driven methods may highlight correlative relationships with drivers without causation.

Likewise, purely qualitative analyses may be limited in their capacity to detect shocks because of differences in reporting across regions. We caution that this approach is not meant to provide a comprehensive list of contributing factors for a given shock within the data, but instead highlights the potential drivers of change from the literature we identify. It is plausible that other unidentified factors contribute to the changes seen in the data.

In our analysis, we classify drivers of shocks into five main categories. Climate/weather events include anomalies such as storms, droughts, El Niño Southern Oscillation events or climate-driven ecosystem change. Geopolitical/economic events include disturbances from conflict, state dissolution or financial crises. Mismanagement includes multiple categories, such as overfishing in the ocean, or deforestation and erosion of soils on land. Policy change can refer to, for example, closure of a fishery or abolition of agricultural subsidies. The 'other' category includes a wide range of pressures from production diseases to geological events, such as tsunamis or volcanic eruptions. Due to the complex nature of social and ecological stressors on food systems, we combined many of these categories to explain the drivers of production shocks and highlight these subcategories. The Unknown category contains shocks for which we could not find a documented reason. It is possible that our statistical approach to detection means we identify changes to national reporting methods as a shock. This highlights the importance of the complimentary quantitative and qualitative approaches used here to identify whether a statistical anomaly in production data is reflected by conditions or events reported in reality[2].

We do, however, acknowledge that some of the detected production losses may not be completely unanticipated. Some production losses driven by economic recession or policy changes may be expected by producers. However, to what extent the production losses detected here were anticipated is unclear because of data scarcity. Policy responses to dwindling resources can certainly produce shocks to food supply and livelihoods, as exemplified in the closure of, and subsequent anger surrounding, the North-West Atlantic cod fishery in 1993[57]. However, even if an event is anticipated, the scale of disruption may be unknown (the uncertainty surrounding the economic impacts of the United Kingdom leaving the European Union is a contemporary example). While the uncertainty surrounding whether a statistical shock in production data equates to a shock in reality is a limitation, this method does allow non-biased detection of shocks caused by drivers for which there are scant data (for example, sudden declines from fish stock collapse). Although sensitivity analyses of Cook's distance, LOESS span or production baseline parameters provided confidence intervals, we may not have detected all of the shocks (Supplementary Fig. 3). Furthermore, the shock detection method described here is less sensitive to production changes in highly variable systems where large fluctuations are common within the time-series[2].

Data availability

Crop and livestock production data were accessed through FAOSTAT (http://www.fao.org/faostat/en/). For marine fisheries production, we used the published dataset by Watson[54] at https://www.nature.com/articles/sdata201739. Aquaculture and inland fisheries data were extracted from global production datasets using FishStat software (www.fao.org/fishery/topic/166235/en). All code and data products used for analyses in this study are publicly available through a GitHub repository (https://github.com/cottrellr/shocks). All data that support this study are available from the corresponding author on request.

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References

1. *Transforming our World: The 2030 Agenda for Sustainable Development* (United Nations General Assembly, 2015).
2. Gephart, J. A., Deutsch, L., Pace, M. L., Troell, M. & Seekell, D. A. Shocks to fish production: identification, trends, and consequences. *Glob. Environ. Change* **42**, 24–32 (2017).
3. Seekell, D. et al. Resilience in the global food system. *Environ. Res. Lett.* **12**, 025010 (2017).
4. *The State of Food Security and Nutrition in the World* (FAO, IFAD, UNICEF, WFP & WHO, 2017).
5. Tadesse, G., Algieri, B., Kalkuhl, M. & von Braun, J. Drivers and triggers of international food price spikes and volatility. *Food Policy* **47**, 117–128 (2014).
6. Marchand, P. et al. Reserves and trade jointly determine exposure to food supply shocks. *Environ. Res. Lett.* **11**, 095009 (2016).
7. Buhaug, H., Benjaminsen, T. A., Sjaastad, E. & Theisen, O. M. Climate variability, food production shocks, and violent conflict in Sub-Saharan Africa. *Environ. Res. Lett.* **10**, 125015 (2015).
8. Dabbadie, L. et al. in *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options* (eds Barange, M. et al.) 449–464 (FAO, 2018).
9. Selkoe, K. A. et al. Principles for managing marine ecosystems prone to tipping points. *Ecosyst. Health Sustain.* **1**, 1–18 (2015).
10. IPCC *Climate Change 2001: Impacts, Adaptation, and Vulnerability* (eds McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. & White, K. S.) (Cambridge Univ. Press, 2001).
11. Fisher, B. et al. Integrating fisheries and agricultural programs for food security. *Agric. Food Secur.* **6**, 1 (2017).
12. Blanchard, J. L. et al. Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nat. Ecol. Evol.* **1**, 1240–1249 (2017).
13. Sartori, M. & Schiavo, S. Connected we stand: a network perspective on trade and global food security. *Food Policy* **57**, 114–127 (2015).
14. Lesk, C., Rowhani, P. & Ramankutty, N. Influence of extreme weather disasters on global crop production. *Nature* **529**, 84–87 (2016).
15. Rao, M. P. et al. Dzuds, droughts, and livestock mortality in Mongolia. *Environ. Res. Lett.* **10**, 074012 (2015).
16. Liu, J. et al. Framing sustainability in a telecoupled world. *Ecol. Soc.* **18**, 26 (2013).
17. Perry, B. D., Grace, D. & Sones, K. Current drivers and future directions of global livestock disease dynamics. *Proc. Natl Acad. Sci. USA* **110**, 20871–20877 (2013).
18. Cottrell, R. S. et al. Considering land-sea interactions and trade-offs for food and biodiversity. *Glob. Change Biol.* **24**, 580–596 (2018).
19. Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D. & Halpern, B. S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl Acad. Sci. USA* **115**, 5295–5300 (2018).
20. Galaz, V., Gars, J., Moberg, F., Nykvist, B. & Repinski, C. Why ecologists should care about financial markets. *Trends Ecol. Evol.* **30**, 571–580 (2015).
21. *Nutrition Country Profile: Republic of Albania* (FAO, 2005).
22. Moutopoulos, D., Bradshaw, B. & Pauly, D. *Reconstruction of Albania Fishery Catches by Fishing Gear* Working Paper 2015-12 (Fisheries Centre, 2015).
23. Cobani, M. *National Aquaculture Sector Overview: Albania* (FAO, 2015); http://www.fao.org/fishery/countrysector/naso_albania/en
24. Noland, M. Famine and reform in North Korea. *Asian Econ. Pap.* **3**, 1–40 (2004).
25. Noland, M., Robinson, S. & Wang, T. Famine in North Korea: causes and cures. *Econ. Dev. Cult. Change* **49**, 741–767 (2001).
26. Kimenyi, M. et al. *The Impact of Conflict and Political Instability on Agricultural Investments in Mali and Nigeria* Working Paper 17 (Africa Growth Initiative, 2014).
27. Matthews, A. Trade rules, food security and the multilateral trade negotiations. *Eur. Rev. Agric. Econ.* **41**, 511–535 (2014).
28. *FAO/WFP Crop and Food Supply Assessment Mission to Afghanistan* (FAO, 2002).
29. Ramdeen, R., Harper, S. & Zeller, D. In *Fisheries Catch Reconstructions: Islands* Volume 22 Part IV 33–41 (Fisheries Centre Research Reports, Univ. British Columbia, 2014).
30. Mohan, P. The economic impact of hurricanes on bananas: a case study of Dominica using synthetic control methods. *Food Policy* **68**, 21–30 (2017).
31. Belhabib, D., Dridi, R., Padilla, A., Ang, M. & Le, P. Impacts of anthropogenic and natural "extreme events" on global fisheries. *Fish Fish.* **19**, 1092–1109 (2018).
32. Bayer, A. M. et al. The 1997–1998 El Niño as an unforgettable phenomenon in northern Peru: a qualitative study. *Disasters* **38**, 351–374 (2014).
33. Schwarz, L. *National Aquaculture Sector Overview: Ecuador* (FAO, 2005); http://www.fao.org/fishery/countrysector/naso_ecuador/en
34. Lafferty, K. D. et al. Infectious diseases affect marine fisheries and aquaculture economics. *Annu. Rev. Mar. Sci.* **7**, 471–496 (2015).
35. Allison, E. & Ellis, F. The livelihoods approach and management of small-scale fisheries. *Mar. Policy* **25**, 377–388 (2001).
36. Van Ginkel, M. et al. An integrated agro-ecosystem and livelihood systems approach for the poor and vulnerable in dry areas. *Food Secur.* **5**, 751–767 (2013).
37. Brashares, J. S. et al. Bushmeat hunting, wildlife declines, and fish supply in West Africa. *Science* **306**, 1180–1183 (2004).
38. Bragina, E. V. et al. Rapid declines of large mammal populations after the collapse of the Soviet Union. *Conserv. Biol.* **29**, 844–853 (2015).
39. Suweis, S. et al. Resilience and reactivity of global food security. *Proc. Natl Acad. Sci. USA* **112**, 6902–6907 (2015).
40. Puma, M. J., Bose, S., Chon, S. Y. & Cook, B. I. Assessing the evolving fragility of the global food system. *Environ. Res. Lett.* **10**, 024007 (2015).
41. Tamea, S., Laio, F. & Ridolfi, L. Global effects of local food-production crises: a virtual water perspective. *Sci. Rep.* **6**, 18803 (2016).
42. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
43. Lipper, L. et al. Climate-smart agriculture for food security. *Nat. Clim. Change* **4**, 1068–1072 (2014).
44. *ViEWS: a Political Violence Early-Warning System* (Uppsala Universitet, 2017); http://www.pcr.uu.se/research/views/
45. Devereaux, S. Social protection for enhanced food security in sub-Saharan Africa. *Food Policy* **60**, 56–72 (2016).

46. Khan, Z. R. et al. Achieving food security for one million sub-Saharan African poor through push–pull innovation by 2020. *Phil. Trans. R. Soc. B* **369**, 20120284 (2014).
47. Hazell, P. B. R. & Hess, U. Drought insurance for agricultural development and food security in dryland areas. *Food Secur.* **2**, 395–405 (2010).
48. Cai, W. et al. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat. Clim. Change* **4**, 111–116 (2014).
49. Marshall, A. Drought-tolerant varieties begin global march. *Nat. Biotech.* **32**, 308 (2014).
50. Fisher, M. et al. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: determinants of adoption in eastern and southern Africa. *Clim. Change* **133**, 283–299 (2015).
51. Stentiford, G. D. et al. New paradigms to help solve the global aquaculture disease crisis. *PLoS Pathog.* **13**, 1–6 (2017).
52. FAOSTAT (FAO, 2017); http://www.fao.org/faostat/en/#data
53. *FishStatJ—Fisheries and Aquaculture Software for Fisheries Statistical Time Series* (FAO, 2017).
54. Watson, R. A. A database of global marine commercial, small-scale, illegal and unreported fisheries catch 1950–2014. *Sci. Data* **4**, 170039 (2017).
55. *Maritime Boundaries Geodatabase* v.10 (Flanders Marine Institute, 2018); https://doi.org/10.14284/312
56. R Core Development Team *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2017).
57. Milich, L. Resource mismanagement versus sustainable livelihoods: the collapse of the Newfoundland cod fishery. *Soc. Nat. Resour.* **12**, 625–642 (1999).

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Author contributions
R.S.C., J.L.B., K.L.N. and B.S.H. designed the study. R.S.C. conducted the analysis and wrote the paper. T.A.R. assisted with the figures. A.J. assisted with qualitative analysis of shock drivers. All authors contributed to development of the paper through methodological advice, comments and edits of the text and figures.

Competing interests
The authors declare no competing interests.

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